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COSMIC CONTINUOUS SPECTRA AND ELECTRON RADIATION

By WOLFGANG FINKELNBURG[1]

ABSTRACT

Continuous radiation emitted by electrons interacting with positive ions must be taken into consideration in explaining many cosmic continuous spectra. The difficulties in calculating the intensity of this radiation are discussed, and it is pointed out that radiation of fast electrons, i.e., electrons whose velocity and number are not in equilibrium with the temperature of their layer, must play an important rôle. The possible influence of this effect on the spectra of the sun, the fixed stars, the corona, the comets, daylight, and some gaseous nebulae is briefly discussed.

A completely satisfactory treatment of the problem of continuous spectra in astrophysics has not been possible up to the present time. In many cases the observations made with very small dispersion do not allow a sufficiently clear comparison with the theory; in other cases, however, there is evidence for a real discrepancy between the observations and the existing theories.

The intensity distribution in the continuous spectra of the sun and the fixed stars apparently does not follow Planck's law. According to Milne,[2] this deviation cannot be accounted for by assuming local thermodynamic equilibrium in the different layers of the atmosphere. There is some uncertainty about the explanation of the continuous spectra emitted by certain groups of gaseous nebulae, especially those with emission lines.[3] The problem of the continuous

[1] Fellow of the Rockefeller Foundation.

[2] *Phil. Trans.* (1), **223**, 201, 1922.

[3] *Handb. der Astroph.*, **5**, Part II, 799, 1933.

spectra of comets has been discussed frequently,[4] but there seems to be no agreement even with respect to the observations. The observations of the continuous spectra of the corona[5] and of the blue skylight[6] give evidence for the assumption that one or more components besides the reflected sunlight contribute to these spectra. Cohn[5, 6] has shown recently that for these spectra also the assumption of Rayleigh scattering of the sunlight does not satisfy all observations, especially those on the degree of polarization.

Cohn therefore assumes the existence of a continuous radiation not previously considered, which he supposes to be produced by electron bombardment, and which he compares with the continuous spectra he produces[7] in bombarding gases at very low pressure and metals, with fast electrons ($v \approx 25{,}000$ volts). He supports his hypothesis that the same process accounts for certain cosmic spectra and for his blue luminescence by two premises. First, the existence of ions and fast electrons at a very low pressure is necessary and sufficient for the production of his luminescence. The same conditions he expects to be present in the corona, in comets, and in the high atmosphere. Second, there seems to be an agreement between the intensity distribution of his continuous luminescence and the "difference-curves" which he gets in subtracting the intensity of the sun's radiation from the observed spectra.

Although we shall show that Cohn's principal assumption of a continuous emission due to electrons is undoubtedly right, his comparison is not quite satisfactory, either from the standpoint of the physicist or from that of the astronomer. In the first place, electrons of such a high velocity as Cohn needs for the production of his blue continuous spectra in high-voltage tubes cannot be expected in the atmosphere of the sun, in comets, or in the high layers of our own atmosphere—at least not in a considerable number.[8] On the other

[4] N. T. Bobrovnikoff, *Ap. J.*, **66**, 145, 439, 1927; W. M. Cohn, *ibid.*, **76**, 277, 1932; F. Baldet, *C.R.*, **199**, 31, 1934.

[5] W. Grotrian, *Zs. f. Ap.*, **8**, 124, 1934; W. M. Cohn, *A.N.*, **245**, 377, 1932.

[6] W. M. Cohn, *Gerlands Beiträge z. Geophysik*, **37**, 198, 1932.

[7] *Zs. f. Phys.*, **70**, 662, 667, 679, 1931; **72**, 392, 1931; **73**, 662, 1932; **75**, 544, 1932.

[8] The mean kinetic energy of an electron even at 10^6 degrees K is only 130 volts. With the exception of a very few much faster electrons due to cosmic-ray ionization, all electron velocities in the solar system should be below this limit.

hand, we have no satisfactory explanation of Cohn's experiments, especially of the intensity distribution in his spectra. This intensity distribution must be explained as a result of his special experimental conditions (electron velocities) and therefore cannot be compared with the conditions in astrophysics where electrons of low velocity certainly play the most important rôle. An agreement between the mentioned difference-curves and the intensity distribution of Cohn's spectra does not allow a decision, therefore, on Cohn's hypothesis.

From a theoretical standpoint we have the following problem: Continuous radiation is emitted by electrons colliding with positive ions, i.e., by changing the direction and velocity of their motion in the field of positive ions. Two cases are possible. If the collision results in a recombination of the ion and the electron, i.e., if we have transitions from Bohr's hyperbolic orbits to elliptic orbits, we observe continuous bands extending from the short wave-length limit of the different line series toward shorter wave-lengths, namely, the free-bound radiation. If, however, the colliding electron leaves the field of the ion again as a free electron (hyperbolic-hyperbolic transitions), we observe free-free radiation, a smooth continuous spectrum extending over a wide range given by the kinetic energies of the colliding electrons. The intensity distribution of these continuous spectra depends on the density and velocity distribution of the ions and electrons, which are seldom known. Furthermore, we must take into consideration the fact that the theory[9] has been carried through only for pure nuclei. We know,[10] however, that there exists a strong individual influence due to the remaining electron shells of the ions, so that a Ca^{++} atom will behave very differently from an O^{++} or a nucleus with the charge 2. Every calculation becomes finally more complicated through the fact that there is also a continuous absorption connected with the electron radiation. For radiating layers of great thickness this results in a considerably changed intensity distribution due to the effect of the different optical depth. This latter effect makes the problem especially difficult in all cases where the principle of detailed balancing does not apply.

[9] E.g., H. A. Kramers, *Phil. Mag.*, **46**, 836, 1923; A. Sommerfeld, *Ann. d. Phys.* **11**, 257, 1931; M. Stobbe, *ibid.*, **7**, 661, 1930; A. W. Maue, *ibid.*, **13**, 161, 1932.

[10] E.g., H. Krefft, *Zs. f. Phys.*, **77**, 752, 1932.

We have shown recently[11] that the continuous radiation emitted by relatively slow electrons ($v < 20$ volts) interacting with positive ions plays a far more important rôle in spectroscopy than is usually assumed. Many continuous spectra emitted by all kinds of condensed sparks, by electric arcs, and by flames are to be interpreted as electron radiation. According to the experimental conditions, the above-mentioned continuous spectra observed by Cohn in his high-vacuum tubes[7] are also to be explained as electron radiation. This last problem has to be studied theoretically in more detail.

The problem which arises now is to what extent does the continuous radiation described here appear in stellar objects. We know that collisions of electrons of sufficiently high velocity with positive ions take place in all cases where continuous spectra are observed in the sky, and the conclusion seems inevitable that continuous electron radiation must be emitted there. Our knowledge of the density and velocity distribution of ions and electrons is, however, in all cases so uncertain that quantitative conclusions seem impossible at the present time. Conclusions from a comparison with the intensity of the discrete spectra also seem difficult because we need more information about the relative importance of electron and photon collisions for the production of stellar spectra. We think it necessary, however, to call attention to the fact that continuous electron radiation must appear and therefore has to be taken into consideration in a theoretical treatment of the cosmic continuous spectra, unless it can be proved that this contribution is too small to be appreciable.

Our actual knowledge seems to be rather scanty. From the observation of the very intensive ionic spectra in the atmosphere of the sun up to its highest layers we know of the existence of a great number of positive ions, and the same applies to the comets. For the earth's atmosphere, especially the observations of the Heaviside layer, gives evidence of a high degree of ionization. The investigations on sun-spots, magnetic disturbances, and the aurora, on the other hand, have made evident the existence of fast[12] electrons strik-

[11] W. Finkelnburg, *ibid.*, **88**, 297, 768, 1934; *Phys. Rev.*, **45**, 341, 1934.

[12] By "fast" we mean here electrons with higher kinetic energy than that corresponding to the Maxwell distribution of the temperature of their layer. Since the mean kinetic energy of an electron at 6000° K (temperature of the photosphere of the sun) is only 0.8 volt, electrons of 10-volt energy are here to be regarded as "fast."

ing the earth's atmosphere and have led to the conclusion that besides the electrons corresponding in number and velocity to the temperature equilibrium of the different layers of the sun, an emission of fast "directed" electrons takes place at least from certain points of the sun. In all these cases, consequently, the conditions for the emission of continuous electron radiation are fulfilled. In gaseous nebulae with emission lines, a continuous spectrum has been observed in only very few cases.[13] In a recent paper G. Cillié[14] computes for nebulae the relative importance of free-free and free-bound transitions for a mixture of protons and electrons in thermodynamic equilibrium and comes to the conclusion that the free-free radiation is of the same order of magnitude as the Balmer-series continuum. The possibility of observing the free-free radiation, however, he thinks is negligible, because the radiation is spread out over a very wide spectral range and the main part of the emission lies in the infra-red. It must be mentioned, however, that besides hydrogen, multiply charged ions of many other elements exist in the nebulae which should not be neglected since the radiation is proportional to the square of the ionic charge. It does not seem improbable that in special cases this radiation may become important and may account for some observed continuous spectra.

An especially interesting problem is the continuous spectrum of the sun and of the fixed stars. In all attempts at a theoretical treatment of their continuous spectra, simplified models have been discussed. In these theories, therefore, the continuous electron radiation is included, in so far as it is emitted by the single layers under the assumption of thermodynamic equilibrium and therefore contributes to the resulting Planck radiation. Consequently, we have only to consider which part of the radiation is emitted by the mentioned faster electrons, i.e., by electrons whose number and velocity do not correspond to the temperature of the layer in which they radiate, and which therefore cannot be included in the theoretical treatment of the usual star models. We expect that the radiation of these directed electrons will not be of great importance in the case

[13] Dr. Stoy has informed me that he has observed many planetary nebulae which emit faint continuous spectra.

[14] *M.N.*, **92**, 820, 1932.

of our sun because of its relatively small turbulent motion. For very turbulent stars, however, like novae, Wolf Rayet stars, and Cepheids, strong eruptions of electrons and ions from the interior may be expected.[15] In the spectra of these stars deviations from the Planck intensity distribution due to continuous emission and absorption of these directed electrons are very probable.

For helpful discussions I am indebted to astronomers and physicists at Mount Wilson and Lick observatories, at the University of California, and at the California Institute of Technology.

NORMAN BRIDGE LABORATORY OF PHYSICS
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA
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[15] An attempt to explain the features of the spectra of novae and Wolf Rayet stars on the assumption of fast particles being emitted from them has recently been made by Chandrasekhar (*ibid.*, **94**, 522, 1934).

PHOTOGRAPHIC MAGNITUDES OF PROPER-MOTION STARS*

By HOWARD C. WILLIS

ABSTRACT

This paper describes the determination of photographic magnitudes on the international scale of 203 stars of large proper motion between magnitudes 8 and 16. The instruments used were the 60-inch reflector and the Ross 5-inch refractor.

Last year S. L. Thorndike[1] published the "Apparent Photographic Magnitudes of 24 Proper-Motion Stars." The present paper gives the results of a continuation of that work, together with the photographic magnitudes of some K- and M-type dwarf stars.

The photographic magnitudes of stars fainter than 10 and of all components of double stars were derived from plates taken at the Newtonian focus of the 60-inch reflector. Two exposures on the star and two on a nearby Selected Area were made on the same plate with the same exposure time. A 32-inch diaphragm with a reduction constant of 1.96 mag. was used on the brighter proper-motion stars in order to make them comparable with the more numerous faint stars in the Selected Areas. The 60-inch aperture was used on the Selected Area fields and on fainter proper-motion stars. Eastman 40 plates were used for all the observations.

Scale readings on ten or fifteen Selected Area stars were corrected for distance error and plotted against the photographic magnitudes given in the *Mount Wilson Catalogue of Photographic Magnitudes in Selected Areas 1–139*.[2] The magnitude corresponding to the mean of the two scale readings for the proper-motion star was read from the curve. This magnitude was corrected for extinction when the differential atmospheric extinction was greater than 0.02 mag. A further correction of 1.96 mag. was applied to values obtained with the 32-inch diaphragm.

The photographic magnitudes of most of the stars brighter than

* *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington*, No. 502.

[1] *Pub. A.S.P.*, **45**, 255, 1933.

[2] *Pub. Carnegie Institution of Washington*, No. 402, 1930.

11 were determined from 5-minute exposures taken slightly intrafocal (0.3 mm) with the Ross 5-inch refractor. The arrangement of the exposures was the same as in the case of the 60-inch reflector. The color correction for the given focal setting and exposure time was derived from exposures on 80 BD stars, photographic magnitudes 8–12, within 2° of the north pole. The magnitudes and color indices used for these stars, which are on the international scale, are from unpublished material by Seares and Ross. The color correction was found to be practically independent of magnitude and equal to 0.2 of the color index. The distance correction has been neglected, as it proved to be less than 0.02 mag. for all stars in the given magnitude range and within 2° of the center of the plate. Fifteen or twenty of the standards, corrected for color, were used in the manner indicated above to determine the magnitudes of the proper-motion stars.

For ten stars, two plates each were taken on different nights with the 60-inch reflector. The average difference between the two values obtained for each of these stars is ±0.08 mag., corresponding to a probable error of ±0.05 mag. for a single observation. Five pairs of plates with the Ross 5-inch indicate for this instrument a similar order of precision.

The results thus found for 203 stars appear in the sixth column of Table I. The spectral types in the seventh column are in general from the manuscript of the new catalogue of spectroscopic parallaxes soon to be published by the Mount Wilson Observatory. Spectral types of the fainter stars inclosed in parentheses are values from low-dispersion spectrograms supplied by Humason.

The parallaxes given in the last column but one are mean values based on the card catalogue of van Maanen, which includes trigonometric parallaxes from the Mount Wilson, Allegheny, McCormick, Yerkes, Sproul, Greenwich, Johannesburg, Cape of Good Hope, and Van Vleck observatories, reduced to absolute values and corrected for systematic errors by van Maanen's[3] tables. Each corrected absolute trigonometric parallax was given unit weight. The weights assigned to the new Mount Wilson spectroscopic parallaxes depend on the size of the parallax. The weighted means of the spectroscopic

[3] *Mt. W. Contr.*, No. 474; *Ap. J.*, **78**, 189–199, 1933.

TABLE I

Star		α 1900	δ 1900	l 1900	b 1900	Pg. m	M.W. Sp.	μ	π	Pg. M
AG Chris	15	$0^h\ 5^m.4$	$+66°35'$	87°	+ 5°	10.4*	K0	0".14	0".014	6.2
20C	16	0 11.8	+40 23	84	−22	10.1†	M0	0.55	.076	9.5
C	90	0 38.2	+33 18	90	−29	9.6*	K5	0.43	.060	8.5
Wolf	33	0 45.3	+57 45	91	− 4	12.5	(M2)	1.58	.062	11.5
Ross	318	0 55.3	+71 9	91	+ 9	11.3	.....	1.76	.085	11.0
C	142	1 0.4	+63 24	92	+ 2	10.2*	M1	1.55	.080	9.7
Ross	322	1 2.2	+33 40	95	−28	14.7	.....	1.52	.055	13.4
C	174	1 15.8	+30 49	99	−30	9.2*	K4	0.50	.032	6.7
Wolf	110	1 57.4	+ 5 14	122	−52	13.4†	.....	2.43	.049	11.8
Ross	17	2 4.2	+34 59	109	−24	15.4	.....	0.74	.....	.....
Wolf	124	2 7.4	+ 3 10	128	−52	11.0	(M4)	2.58	.....	.....
Wolf	125	2 8.2	+15 31	119	−42	14.2	.....	1.08	.004	7.2
$h\chi$ Per	1166	2 10.5	+56 39	102	− 4	13.6	.....	0.17	.007	7.8
Ross	19	2 13.0	+34 54	110	−23	14.5	.....	0.82	.048	12.9
C	298	2 14.0	+70 43	97	+10	9.9*	K8	0.62	.040	7.9
C. Boss	588	2 30.8	+ 6 24	132	−46	13.3	(M4)	2.30	.....	.....
BD	+48°739	2 36.2	+48 34	109	− 9	10.9*	K8	0.38	.043	9.0
Wolf	1323	2 45.8	+34 0	118	−21	10.9	.....	1.37	.074	10.3
ADS	2218B	2 49.7	+26 28	123	−27	10.9	M1	0.33	.076	10.3
20C	194	2 50.3	+52 5	110	− 5	10.1*	K2	0.44	.021	6.7
Wolf	134	3 7.6	+18 29	132	−31	15.4	.....	1.74	.046	13.7
Wolf	1324	3 9.9	+37 45	120	−15	11.8	.....	1.36	.....	.....
C	431	3 10.8	+30 40	125	−21	10.4	K5	0.28	.027	7.6
Ross	34	3 22.2	+37 3	122	−15	12.0	.....	1.58	.....	.....
Ross	585	3 24.4	+33 43	125	−17	14.2	.....	1.41	.022	10.9
Boss	823B	3 31.7	+ 0 16	153	−40	10.0	K5	0.15	.037	7.8
Ross	578	3 33.4	−11 46	167	−46	14.6	.....	3.30	.062	13.6
Wolf	219	3 38.8	+18 9	139	−27	15.1	.....	1.25	.078	14.6
Wolf	227	3 47.0	+16 44	141	−26	15.5	.....	0.99	.....	.....
Ross	25	3 52.8	+50 49	118	0	14.9	.....	0.72	.....	.....
Ross	591	3 59.7	+32 44	131	−13	10.8	.....	1.08	.....	.....
Ross	28	4 5.3	+52 22	118	+ 2	15.0	.....	0.90	.057	13.8
BD	+14°699	4 22.1	+14 12	149	−22	10.5	K4	0.07	.025	7.5
20C	296	4 27.9	+55 13	119	+ 6	9.0*	K4	0.63	.069	8.2
C	594	4 29.8	+52 42	121	+ 5	10.0*	M1	0.53	.096	9.9
Ross	33	4 37.0	+18 47	148	−16	11.2	.....	1.27	.116	11.5
vM	5	4 53.2	+39 13	134	0	13.1	.....	0.38	.005	6.6
Ross	41	5 22.6	+ 9 35	163	−13	14.2	.....	0.89	.107	14.3
ADS	4099B	5 23.3	+54 35	124	+12	10.6	K3	0.41	.018	6.9
Ross	47	5 36.4	+12 29	161	− 8	12.7	(M3)	2.53	.166	13.8
Ross	49	5 39.4	+ 9 13	165	− 9	12.3	.....	0.61	.....	.....
Ross	60	5 57.6	+26 10	152	+ 3	15.1	.....	0.78	.....	.....
C	761	5 59.7	+26 34	152	+ 4	10.5*	K8	0.43	.024	7.4
Ross	62	6 2.8	+26 35	153	+ 4	14.9	.....	0.71	.....	.....
71 Ori D		6 8.9	+19 11	160	+ 3	12.5	.....	.....	0.009	7.3

TABLE I—*Continued*

Star		α 1900	δ 1900	l 1900	b 1900	Pg.m	M.W. Sp.	μ	π	Pg.M
C	783	$6^h10^m.5$	+25°15′	154°	+ 5°	10.2*	K8	0″.45	0″.043	8.4
Ross	64	6 18.5	+23 30	157	+ 6	14.5	.....	0.49	.....	.....
C	803	6 22.9	+27 5	154	+ 9	9.2*	K4	0.51	.040	7.2
Ross	614	6 24.3	− 2 44	180	− 5	12.6	.....	0.97	.....	.....
20C	393	6 31.5	+17 38	163	+ 6	10.9	M1	0.84	.099	10.9
C	837	6 49.5	+40 13	144	+19	9.8	Mo	0.44	.038	7.7
Comp. to C	837	6 49.5	+40 14	144	+19	12.2	.....	0.43	.029	9.5
Ross	54	6 59.6	−10 21	191	− 1	12.8	.....	0.82	.....	.....
20C	418	7 13.0	+33 2	153	+21	11.5*	M2	0.56	.058	10.3
C	884	7 17.7	+46 18	140	+26	10.1*	K2	0.45	.021	6.7
20C	439	7 40.8	+53 54	131	+31	10.0‡	K8	0.56	.036	7.8
Wolf	1421	7 42.2	+20 39	168	+23	12.7	.....	1.77	.078	12.2
C	977	8 12.0	+30 56	159	+33	9.9*	K8	0.87	.050	8.4
20C	473	8 18.9	+32 57	157	+34	11.0*	K8	0.64	.038	8.9
20C	474	8 22.5	+46 15	142	+37	11.0*	K8	0.50	.033	8.6
20C	475	8 27.4	+67 38	114	+36	10.6*	Mo	1.09	.080	10.1
20C	490	8 43.0	+36 53	154	+40	11.9	M1	0.56	.039	9.9
Ross	682	8 43.1	+ 6 51	189	+30	11.2	(K8)	0.55	.032	8.7
Ross	623	8 50.0	+ 1 57	195	+29	10.8	.....	1.09	.067	9.9
Ross	87	9 18.0	+29 0	166	+46	12.1	.....	0.50	.....	.....
Ross	83	9 20.0	+19 7	180	+44	14.3	.....	0.60	.066	13.4
20C	532	9 25.8	+36 46	155	+49	11.6§	M2	0.55	.072	10.9
Ross	84	9 25.9	+20 44	178	+46	13.5	.....	0.78	.....	.....
Ross	90	9 32.7	+22 28	176	+47	14.8	.....	0.84	.....	.....
Ross	92	9 35.4	+22 29	177	+48	15.7	.....	0.72	.....	.....
C	1163	9 43.5	+14 14	190	+47	8.5*	A4sp	0.86	.022	5.2
C	1167	9 46.2	−11 49	217	+32	11.3*	M2	1.85	.084	10.9
20C	553	9 48.8	+63 16	116	+46	10.5*	M1	0.69	.074	9.9
Ross	96	9 49.7	+22 58	178	+52	14.2	.....	0.64	.....	.....
C	1225	10 7.5	+53 1	128	+52	10.6*	Mo	0.75	.047	9.0
C	1244	10 14.2	+20 22	185	+56	10.9	M4e	0.49	.212	12.5
Ross	446	10 23.8	+ 1 22	213	+48	11.0	.....	0.96	.113	11.3
20C	582	10 25.5	+46 3	137	+58	10.2*	M1	0.84	.062	9.2
Ross	99	10 30.1	+ 8 3	207	+53	13.1	.....	0.61	.....	.....
Ross	626	10 41.9	+28 57	171	+64	10.7	.....	0.48	.....	.....
Ross	107	10 49.8	+56 34	116	+55	13.8	.....	0.56	.059	12.7
20C	599	10 51.4	+42 25	140	+64	10.5*	K3	0.79	.020	7.0
C	1349	11 0.5	+44 2	135	+64	10.1*	M2	4.54	.173	11.3
Wolf	365	11 5.9	+ 6 59	219	+59	11.6	.....	0.82	.026	8.7
C	1383	11 14.8	+66 23	103	+50	10.7*	M1	2.99	.106	10.8
20C	630	11 17.1	+15 0	120	+63	11.0	Ko	0.57	.011	6.2
Ross	627	11 19.1	+21 55	194	+71	14.1	.....	1.23	.....	.....
Ross	110A	11 22.9	+57 17	110	+58	15.5	.....	0.70	.....	.....
Ross	110B	11 22.9	+57 17	110	+58	15.9	.....	0.70	.....	.....
C	1412	11 23.3	+ 8 6	224	+63	10.6	G7	1.21	0.013	6.1

TABLE I—*Continued*

Star	α 1900	δ 1900	l 1900	b 1900	Pg.m	M.W. Sp.	μ	π	Pg.M
Boss 3032B	11h26m6	+14°55′	214°	+69°	10.2	K8	0″38	0″050	8.7
Ross 114	11 31.4	+14 7	218	+69	14.3	.....	0.53	.....	.....
20C 654	11 33.7	+42 52	127	+70	9.0*	K5	0.46	.052	7.6
Ross 128	11 42.6	+ 1 23	240	+60	12.7	.....	1.40	.....	.....
Ross 119	11 49.0	+10 23	234	+68	14.1	.....	0.73	.....	.....
Ross 129	11 50.1	+ 1 32	244	+61	13.3	.....	0.69	.....	.....
Ross 122	11 52.5	+12 23	231	+71	12.8	.....	0.77	.....	.....
Wolf 1426	11 56.2	+23 30	202	+79	14.1	.....	0.63	.....	.....
Wolf 406	12 3.3	+ 0 3	251	+61	12.4	.....	0.96	.058	11.2
Wolf 1434	12 4.1	+20 0	222	+79	12.5	.....	0.48	.032	10.0
Wolf 1435	12 4.5	+ 8 57	244	+69	14.7	.....	0.81	.....	.....
Wolf 1438	12 8.4	+17 16	234	+77	13.3	.....	0.65	.....	.....
Wolf 1440	12 12.2	+21 37	224	+81	12.8	.....	0.74	.....	.....
20C 695	12 14.4	+28 56	168	+84	11.6	M2	0.64	.042	9.7
Wolf 1441	12 14.5	+ 6 13	253	+67	13.2	.....	0.43	.....	.....
Ross 695	12 19.6	−17 38	263	+44	12.4	.....	2.49	.....	.....
20C 713	12 26.3	+ 9 22	260	+71	11.1*	M1	0.84	.057	9.9
Wolf 1447	12 29.4	+15 49	257	+78	12.1	.....	0.35	.....	.....
Wolf 433	12 34.0	+12 15	265	+74	12.8	(M3)	1.16	.072	12.1
BD +84°284	12 36.1	+84 11	90	+34	10.8*	K1	0.20	.014	6.6
Luyten 1787	12 51.5	+16 17	280	+78	14.4	.....	1.50	.....	.....
Wolf 457	12 55.1	+ 4 2	279	+66	15.6	.....	1.05	.....	.....
ADS 8861A	13 14.9	+35 40	49	+79	10.9	M1	0.88	.084	10.5
ADS 8861B	13 14.9	+35 40	49	+79	13.4	.....	.....	.....	.....
Ross 490	13 24.9	+10 55	304	+70	10.6	.....	1.49	.120	11.0
20C 795	13 36.8	+ 0 23	298	+59	11.0*	M1	0.42	.....	.....
20C 808	13 42.5	+ 6 49	308	+64	11.0	Mo	0.54	.027	8.2
20C 825	13 54.8	+34 21	25	+73	10.6	A4sp	0.54	.017	6.8
Ross 848	14 14.8	− 9 9	305	+46	14.4	.....	1.09	.....	.....
C 1885	14 17.6	+30 6	11	+69	9.9‡	Mo	0.74	.075	9.3
βGC 6869A	14 21.1	+24 6	356	+67	10.8	M1	1.39	.072	10.1
βGC 6869B	14 21.1	+24 6	356	+67	11.1	M2	1.40	.076	10.5
20C 860	14 23.3	+24 18	356	+67	11.6	Mo	0.49	.026	8.7
C 1920	14 30.9	+34 11	21	+65	10.7	Mo	0.76	.066	9.8
ADS 9346B	14 38.2	+58 23	64	+53	9.2	G7	0.24	.019	5.6
C 1948	14 41.7	+16 57	345	+60	10.5‡	K8	0.95	.054	9.2
Ross 53	14 53.5	+31 46	16	+61	12.0	.....	1.50	.....	.....
C 2012	15 3.1	+25 18	3	+58	11.2	Mo	0.98	.055	9.9
20C 920	15 8.8	− 3 26	325	+42	10.7	Mo	0.78	.038	8.6
20C 923	15 14.2	− 7 21	322	+39	12.1	M5	1.32	.161	13.1
Wolf 611	15 52.2	+ 5 26	343	+39	16.1	.....	1.54	.038	14.0
20C 968	16 2.9	+34 55	22	+47	11.4†	Mo	0.64	.048	9.8
20C 986	16 21.1	+48 36	41	+43	11.7	(M3)	1.23	.129	12.3
20C 995	16 24.7	−12 24	331	+22	11.2	M5	1.24	.269	13.4
BD +31°2877	16 33.4	+31 25	19	+40	10.6	K5	.....	0.032	8.1

TABLE I—*Continued*

Star		α 1900	δ 1900	l 1900	b 1900	Pg.m	M.W. Sp.	μ	π	Pg.M
Wolf	629	$16^h50^m.0$	− 8° 8′	339°	+20°	13.2¶	(M4)	1″.26	0″.161	14.2
C	2251AB	16 50.1	− 8 9	339	+20	10.4	M3e	1.24	.142	11.2
20C	1014	16 54.1	+25 55	14	+34	11.0†	M2	0.56	.078	10.5
C	2278	17 0.0	− 4 56	343	+19	11.2	M3	1.44	.096	11.1
ADS	10338B	17 2.3	+47 6	40	+36	11.9	.....	0.05	.....	.....
Anon.		17 29.0	+16 22	7	+23	14.9	.....	0.29	.011	10.1
C	2347	17 33.4	+18 37	10	+23	11.2	M1	1.35	.101	11.2
C	2348	17 33.9	+18 37	10	+23	10.4‡	F1s	0.28	.010	5.4
20C	1051	17 34.5	+61 45	58	+32	11.1	.....	0.57	.....	.....
C	2354	17 37.0	+68 20	65	+32	10.7*	M3	1.33	.214	12.3
Ross	133	17 37.4	−18 28	336	+ 4	13.5	.....	0.56	.....	.....
Boss	4497B	17 42.5	+27 47	20	+25	11.2	M3	0.82	.100	11.2
Wolf	1405	18 0.4	+48 28	43	+27	11.1	.....	0.22	− .003	.....
Wolf	1409	18 5.8	+52 46	48	+27	13.6	.....	0.43	.048	12.0
Wolf	834	18 11.3	+20 29	15	+15	14.6	.....	1.00	.....	.....
Ross	136	18 17.3	+ 6 17	3	+ 8	13.8†	.....	1.20	.091	13.6
ADS	11292A	18 17.6	+11 24	8	+10	10.6	.....	.....	− .007	.....
ADS	11292B	18 17.6	+11 24	8	+10	12.0	.....	.....	.001	1.5
ADS	11576A	18 37.1	+31 28	28	+15	9.3	K4	0.85	.033	6.9
ADS	11576B	18 37.1	+31 28	28	+15	13.0	.....	.....	.....	.....
C	2463	18 44.5	+17 20	16	+ 7	10.4*	M1	0.58	.062	9.4
C	2475	18 53.1	+ 5 48	7	0	10.7*	M1	1.26	.082	10.3
C	2483	18 56.4	+18 57	19	+ 5	10.6*	G4	0.62	.009	5.4
20C	1123	18 57.7	−13 42	350	−10	16.3	.....	0.80	.075	15.7
17 Lyrae C		19 3.7	+32 21	32	+10	12.9†	(M3)	1.66	.127	13.4
Wolf	1062	19 7.0	+ 2 44	6	− 4	12.7	.....	1.88	.109	12.9
Ross	652	19 12.1	+ 5 2	8	− 5	10.7	.....	1.44	.174	11.9
20C	1145	19 15.7	+41 28	41	+12	9.5*	K1	0.66	.024	6.4
Ross	163	19 17.8	+28 28	29	+ 5	12.9†	.....	0.89	.053	9.5
ADS	12594B	19 29.0	+20 12	23	− 1	10.0	.....	0.06	.006	3.8
C	2556	19 29.6	+ 4 21	10	− 9	11.0	M1	0.58	.079	10.5
Boss	5051B	19 42.6	+33 30	36	+ 4	9.6	K8	0.45	.047	8.0
ADS	13434A	20 5.0	+16 30	25	−10	8.6	G9	0.17	.036	6.4
ADS	13434B	20 5.0	+16 30	25	−10	11.2	.....	.....	.....	.....
BD	+38°4048	20 19.0	+38 9	44	0	10.7*	K3	.....	.021	7.3
Wolf	1346	20 30.1	+24 44	35	+10	11.2†	.....	0.68	.056	9.9
20C	1223	20 37.2	−19 16	355	−34	11.6	.....	1.15	.....	.....
Wolf	896	20 51.4	−10 48	6	−34	12.9	.....	1.14	.073	12.2
Ross	193	20 51.5	− 5 14	12	−31	13.3	.....	0.82	.068	12.5
Wolf	1373	20 52.9	+21 59	36	−16	13.5	.....	0.87	.....	.....
Wolf	918	21 3.7	−13 40	4	−38	12.2	(M3)	2.68	.073	11.5
Ross	770	21 7.9	−19 44	358	−41	12.4	.....	1.08	.....	.....
Ross	197	21 15.3	+51 59	61	+ 2	13.1†	.....	0.57	.023	9.9
Anon.		21 24.3	+11 43	33	−28	11.6	.....	0.50	0.033	9.2
Ross	775	21 24.8	+17 12	38	−25	11.9	.....	1.07	.....	.....

TABLE I—*Continued*

Star		α 1900	δ 1900	l 1900	b 1900	Pg.m	M.W. Sp.	μ	π	Pg.M
Wolf	922	2^h25^m8	$-10°13'$	12°	$-41°$	13.0	(M_3)	1".22	0".171	14.2
Ross	200	21 36.6	+53 41	65	+ 1	14.2	.....	0.60	.039	12.2
Ross	206	21 36.7	−12 37	10	−45	13.8	.....	0.66	.068	13.0
Wolf Anon.		21 51.0	+47 52	63	− 5	12.6	.....	0.70	.....	.....
Wolf	1337	21 54.8	− 1 8	27	−42	13.5†	.....	0.39	.023	10.3
Wolf	1340	21 57.1	+ 0 56	30	−41	10.5	.....	0.55	.....	.....
Wolf	1329	22 4.4	− 5 8	25	−47	11.8	.....	0.80	.....	.....
C	2889	22 5.9	+22 18	49	−27	10.1*	K4	0.58	.020	6.6
Wolf	1014	22 7.6	+ 8 5	39	−39	13.1	.....	0.73	.029	10.4
C	2908	22 13.8	+67 50	77	+ 9	10.3	K8	0.37	.057	9.1
BD	+60°2412	22 31.4	+60 17	75	+ 2	10.0	K5	0.09	.033	7.6
C	2986	22 47.3	+31 12	64	−25	10.6*	K8	0.50	.032	8.1
Ross	780	22 47.9	−14 47	21	−61	11.5	.....	1.12	.....	.....
Ross	226	22 50.5	+60 28	77	+ 1	14.2	.....	0.67	.073	13.5
Ross	671	22 51.8	+16 2	56	−39	10.0	.....	1.09	.155	11.0
C	3002	22 55.1	+68 29	81	+ 8	9.6*	K0	0.66	.012	5.1
Wolf	1039	23 29.0	− 0 21	55	−57	12.6	(M_4)	1.44	.065	11.7
Wolf	1040	23 31.6	+ 0 37	57	−57	14.2	.....	1.23	.066	13.3
Ross	248	23 37.0	+43 39	78	−17	14.0	($M6$)	1.82	.319	16.5
Ross	249	23 43.0	+48 27	80	−12	13.5	.....	0.58	.077	12.9
C	3124	23 44.0	+ 1 52	63	−57	10.5*	M_2	1.39	.154	11.4
C	3143	23 53.5	+46 10	82	−15	11.2*	M_0	0.64	.061	10.1
20C	1467	23 54.2	−17 30	42	−75	9.7	G6	1.19	0.014	5.5

NOTES TO TABLE I

* 5-inch Ross refractor.

† Observed on two nights, 60-inch reflector; the respective magnitudes are: 20C 16, 10.17, 10.11; Wolf 110, 13.34, 13.36; 20C 968, 11.40, 11.38; 20C 1014, 10.97, 11.02; Ross 136, 13.85, 13.73; 17 Lyrae C, 12.90, 12.97; Ross 163, 12.87, 12.97; Wolf 1346, 11.25, 11.09; Ross 197, 13.04, 13.10; Wolf 1337, 13.46, 13.57.

‡ Observed on two nights, 5-inch refractor; the respective magnitudes are: 20C 439, 10.04, 10.00; C 1885, 9.94, 9.86; C 1948, 10.36, 10.58; C 2348, 10.37, 10.35.

§ Observed on one night each at the 5-inch Ross refractor and 60-inch reflector; the respective magnitudes are: 11.67, 11.58.

‖ Observed on two nights at the 5-inch Ross refractor and one night at the 60-inch reflector; the respective magnitudes are: 11.04, 11.12, 10.97.

¶ S. L. Thorndike also gives 13.2 as the photographic magnitude of this star.

and the trigonometric parallaxes are given in Table I. The absolute photographic magnitudes in the last column of the table are derived from the adopted mean parallaxes and the observed apparent photographic magnitudes in the sixth column.

These results are given uniformly to the nearest 0.1 mag. It should be noted, however, that the error in M arising from an error $\delta\pi$ in π is $2.2\ \delta\pi/\pi$. For small trigonometric values of π the uncertainty in M is large; and if $\pi \leqslant 0''.02$, the calculated M is only a general indication of the absolute magnitude. For spectroscopic parallaxes the uncertainty in M is less serious.

The galactic longitudes and latitudes were interpolated from Ohlsson's tables,[4] based on the galactic pole at right ascension 12^h40^m, declination $+28°$ (1900).

Proper motions larger than 0.4 per year were taken from *Cincinnati* 20.

CARNEGIE INSTITUTION OF WASHINGTON
MOUNT WILSON OBSERVATORY
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[4] *Annals of the Observatory of Lund*, No. 3, 1932.

FORMATION OF GALAXIES, STARS, AND PLANETS*

By GUSTAF STRÖMBERG

ABSTRACT

The *galaxy* is supposed to have been *formed* from a *primordial* gas, extending to distances greater than its present dimensions. The original motions in the gas may be of any kind; in any case, continuous, fluid motion will gradually be established, owing to viscous forces, if the mean free path of the particles of which the gas is composed is smaller than the dimensions of the system. The hydrodynamical laws can then be applied. This implies also that the particles are exceedingly small (atoms or molecules). It is assumed that an approximately steady state of motion is developed, such that the velocities everywhere can be regarded as a finite, continuous, and single-valued function 8-31-8-25 Bernhardt 11-22-34 L55-L58-Dec Astro-00-Stromberg-Wilson-Williams 1—7 of position, and that the terms defining the explicit dependence on the time are small in comparison to the inertia terms. It is shown that, if these conditions are satisfied, and if we follow a portion of the gas in its motion, its scalar velocity does not change with time. The motions—at least in the interior of the system—are such that the system contracts, generally or locally. At the surface there is a loss of matter owing to escape of particles. The contraction proceeds until the gas has developed into one or more bodies. If the system originally had a finite angular momentum, the bodies formed rotate in the same direction as the system.

If the system has symmetry about the axis of rotation, the motions in the gas are circular in parallel orbits. If smaller condensations are formed before the larger ones have been developed, the system is very flat. The stars formed after the steady state has been reached also move in circles about the axis and in a common plane. Stars formed before this state was reached may have any rotation and any motion, but the velocity must be less than that of escape.

If the relative motion of *two massive condensations* is circular, then, as long as the gaseous envelope has sufficient density, the motions in the gas are along "surfaces of zero relative velocity" with constant scalar velocity. Smaller bodies formed from this envelope move in the same way, but only bodies formed close to a primary can retain this motion after viscous forces and pressure gradients are no longer acting. It is suggested that retrograde satellites are either captured or formed from the gas when in a locally stable state of retrograde motion corresponding to a near coalescence of the two loops in the known periodic orbits in the problem of three bodies.

Application of the theory to the *solar system* indicates that the planets were not formed *in situ* but at great distances from the sun. The theory seems to account for the existence of nearly circular orbits for the massive planets and for the general behavior of the motions of the asteroids and the satellites. If the gas from which the planets were formed was once in the interior of the sun, it may have been expelled either during an encounter with another star or during an explosion like that of a nova. On the first alternative, planetary systems are very rare; on the second, they are a very common phenomenon in the universe.

INTRODUCTION

In *Mount Wilson Contribution* No. 492[1] the writer has attempted to explain the observed facts of stellar motions, in particular the

* *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington*, No. 503.

[1] *Ap. J.*, **79**, 460, 1934.

predominance of circular orbits, the asymmetry in stellar motions, and the relationship between the motions and the physical properties of the stars, as results of viscous forces acting during the general contraction of a very large system, the stars being formed by local condensations in the primordial gas. After the paper had been sent to press, Lindblad's[2] article appeared, dealing partly with the same problem. Lindblad studies the problem from a different viewpoint, but his principal results are the same, namely, that in a system with axial symmetry, in which the density increases toward the center, we may expect circular "planetary" orbits in a common plane of motion. He emphasizes the fact that the escape of particles at the surface contributes greatly to the general contraction of the system. Although he does not explicitly introduce viscous forces, his analysis has certain things in common with that of fluid motion. To the present writer it seems that the motions of the stars are determined by conditions existing *at the time of their formation*, and that the problem can only be studied by regarding the primordial gas as a viscous, compressible fluid and by finding the probable development of such a fluid. In doing this opportunities will arise for a further explanation of some of the results in *Contribution* No. 492.

Let us think of a "gas" consisting of small "particles" freely hovering in space. The particles may be atoms, molecules, or dust particles; but any volume we study must include a great number of them, in order that statistical laws may be applied. Under what conditions may we regard such a gas as a "fluid" in the hydrodynamic sense? The particles are, in general, in motion, owing to the general attractions in the system; and we can certainly apply the concept of viscosity to the gas, since this implies nothing but a mixing of particles in adjacent regions, resulting in a transfer of momenta. The longer the mean free path and the greater the velocity dispersion ("temperature"), the more freely does the mixing take place and the greater is the coefficient of kinematic viscosity. This circumstance may or may not produce "continuous" motion like that in a fluid. If the mean free path is much greater than the dimensions of the system, each particle will describe an independent orbit and no continuous motion will result from the mixing. We must hence assume

[2] *M.N.*, **94**, 231, 1934.

that the mean free path is small compared with the dimensions of the system, which implies the assumption that the particles are exceedingly small, probably of the size of atoms or molecules.[1] The velocity of a particle is then little changed between collisions, which is a necessary condition for the applicability of the hydrodynamic laws.[3] Under these conditions the gradient of the gas pressure is a force acting on the particles themselves.

Darwin[3] was probably the first to realize fully the importance of viscous forces in the development of cosmic systems. On account of the high viscosity, most writers have assumed that the final steady state of the fluid is a rotation as a solid, although Jeans[4] has shown that, in the interior of the stars at least, we must have an angular velocity which decreases outward. The further development of a fluid with constant angular velocity has been extensively studied by many prominent investigators. In this case, the dissipation function, which is never negative, has reached its ultimate minimum, which is zero. But we know from the work of Helmholtz[5] and Korteweg[6] that, if the inertia terms can be neglected, the motions in a viscous, incompressible fluid, with fixed boundary conditions incompatible with rigid-body motion, can reach a steady state in which the dissipation function is a minimum greater than zero. Lord Rayleigh[7] has generalized Korteweg's theorem to include velocities of any size by "introducing" forces parallel to the vector product of the linear and angular velocities. From these results we see that it is important to consider the developments in the fluid previous to the establishment of rigid-body motion.

STEADY MOTIONS IN A COMPRESSIBLE VISCOUS FLUID

In most applications of the hydrodynamics of viscous fluids it has been assumed that the fluid is incompressible and that the coeffi-

[3] Cf. G. H. Darwin, "On the Mechanical Conditions of a Swarm of Meteorites and on Theories of Cosmogony," *Scientific Papers*, **4**, 391, 1889.

[4] *M.N.*, **86**, 328, 444, 1926.

[5] "Zur Theorie der stationären Ströme in reibenden Flüssigkeiten," *Wissenschaftliche Abhandlungen*, **1**, 223, 1882.

[6] *Phil. Mag.* (5th Ser.), **16**, 112, 1883.

[7] *Ibid.*, **36**, 354, 1893.

cient of viscosity is constant throughout the fluid. We cannot make either of these assumptions. Hardly anything has been done on the motions in compressible fluids of variable viscosity. Knowing the mathematical difficulties in studying, for instance, the figures of equilibrium for incompressible fluids of constant angular motion, it may at first sight seem as if we could make little or no headway in the more general case. But in the absence of forces at the boundary the fluid can adapt itself to the gravitational forces, which are the only forces we shall consider, and it will be found that it is then possible to establish some general relations which are important for a study of the development of such a fluid.

Using Stokes's expressions for the stresses in a viscous fluid element, we can write down the equations of motion of an element of unit volume:

$$\left.\begin{aligned} \rho\left(\frac{Du}{Dt}+\frac{\partial G}{\partial x}\right)&=\frac{\partial p_{xx}}{\partial x}+\frac{\partial p_{yx}}{\partial y}+\frac{\partial p_{zx}}{\partial z}=-\frac{\partial p'}{\partial x}+\mu\nabla^2 u \\ &\quad+\left(2\frac{\partial u}{\partial x}-\Theta\right)\frac{\partial \mu}{\partial x}+\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\frac{\partial \mu}{\partial y}+\left(\frac{\partial w}{\partial x}+\frac{\partial u}{\partial z}\right)\frac{\partial \mu}{\partial z}\,; \\ p'&=p-\frac{\mu\Theta}{3}\,; \qquad \Theta=\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\,. \end{aligned}\right\} \tag{1}$$

In this equation, u, v, and w are the velocity components in an inertial reference frame, ρ the density, p the static pressure, μ the coefficient of viscosity, Θ the divergence, and p_{xx}, p_{yx}, p_{zx}, the components of the stress tensor. The factor $1/3$ occurring in p' implies the assumption that the pressure depends only upon the density and temperature of the gas and not upon the rate of expansion.[8] The other two equations of motion can be found by cyclic permutations.

In the beginning the motions in the fluid may be of any type. Large or small vortices, vortex sheets, and vortex rings may develop and be dissipated, and the temperature may be distributed in an irregular fashion, giving rise to convection currents and escape of particles of high velocity. If at any one point the gradient of the angular velocity is abnormally high, a large part of the gross motion will be

[8] Cf. Lamb, *Hydrodynamics* (3d ed., 1906), pp. 534, 586.

converted into heat motion, the temperature will rise at that point, the coefficient of viscosity will increase, and the dissipation of mechanical energy into heat motion may for a time proceed at an accelerated rate. We shall first suppose that all the heat generated by friction is retained as heat motion in the system and that no energy is lost or gained in the form of radiation or by subatomic processes.

When the fluid is compressible, we have no reason to believe that any unique steady state of motion exists. For instance, the fluid may contract uniformly or locally in a way we cannot predict. We shall assume, however, that "continuous" motion will gradually be established. We will also limit ourselves to those cases for which a co-ordinate system exists such that the motions referred to this system are nearly steady. For convenience we will call this a "steady" state of motion. When it is necessary to take into account the change in motion at any particular place, we shall assume that the terms depending on the partial time-derivatives of the properties of the system are everywhere small relative to the inertia terms. The theory is hence applicable to systems in which there are progressive changes in density, temperature, and pressure, as well as to systems the properties of which are subject to periodic changes, although these changes must always be sufficiently slow. On account of the condition of continuity and steadiness of the motion, we can regard the velocity vector, if referred to the proper co-ordinate system, as a continuous, finite, and single-valued function of position, containing also small terms changing slowly with the time.

On account of the progressive change in density, it is convenient to reduce the equations of motion in (1) to unit mass. We write them in the form

$$\frac{Du}{Dt}+\frac{\partial G}{\partial x}=\frac{1}{\rho}\left(\frac{\partial p_{xx}}{\partial x}+\frac{\partial p_{yx}}{\partial y}+\frac{\partial p_{zx}}{\partial z}\right)=f_x\,, \tag{2}$$

with similar equations for the y and z components, where f_x, f_y, and f_z are the components of the accelerations due to pressure gradients and to viscous drag.

Let us study a portion of the fluid which at time t occupies a rectangular volume element $dxdydz$ having its center at x, y, z. Calcu-

lating the rate at which work is being done by the tractions on the pairs of opposite faces, we obtain[9]

$$\left[\frac{\partial}{\partial x}(p_{xx}u+p_{xy}v+p_{xz}w)+\frac{\partial}{\partial y}(p_{yx}u+p_{yy}v+p_{yz}w)\right.$$
$$\left.+\frac{\partial}{\partial z}(p_{zx}u+p_{zy}v+p_{zz}w)\right]dx\,dy\,dz=(A+B)dx\,dy\,dz\,,$$

in which A and B are defined by the equations:

$$A=\left(\frac{\partial p_{xx}}{\partial x}+\frac{\partial p_{yx}}{\partial y}+\frac{\partial p_{zx}}{\partial z}\right)u+\left(\frac{\partial p_{xy}}{\partial x}+\frac{\partial p_{yy}}{\partial y}+\frac{\partial p_{zy}}{\partial z}\right)v+\left(\frac{\partial p_{xz}}{\partial x}+\frac{\partial p_{yz}}{\partial y}+\frac{\partial p_{zz}}{\partial z}\right)w\,, \quad (3)$$

$$B=p_{xx}\frac{\partial u}{\partial x}+p_{yy}\frac{\partial v}{\partial y}+p_{zz}\frac{\partial w}{\partial z}+p_{xy}\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)+p_{xz}\left(\frac{\partial w}{\partial x}+\frac{\partial u}{\partial z}\right)+p_{yz}\left(\frac{\partial w}{\partial y}+\frac{\partial v}{\partial z}\right). \quad (4)$$

A represents the rate at which the tractions on the faces of an element of unit volume are doing work in increasing its kinetic and gravitational energy. B is the rate at which work is being done in producing changes in the volume and the shape of the element, which result in changes in its temperature, density, and pressure. We may also say that A is the rate at which the gross mechanical energy increases, while B is the rate at which the microscopic energy increases. Putting $A+B=C$, we see that C is the rate per unit volume at which the total energy is increased.

The "surface" of the body of fluid is defined by a negligible density; and since there are no tractions on this surface, we must have

$$\iiint C\,dx\,dy\,dz=\int\frac{C}{\rho}\,dm=0\,. \quad (5)$$

C is hence positive in some regions and negative in others, and on the average equal to zero. It is known that B is, in general, positive. A is thus a predominantly negative quantity.

Multiplying equations (2) by u, v, and w, respectively, and introducing equation (3), we obtain the equation for the conservation of energy:

$$\left.\begin{aligned}\frac{D}{Dt}(T+G)=uf_x+vf_y+wf_z=\frac{A}{\rho}=-\varphi\,,\\ 2T=u^2+v^2+w^2\,.\end{aligned}\right\} \quad (6)$$

[9] Lamb, *op. cit.*, p. 540.

The function φ is predominantly positive and represents the rate *per unit mass* at which mechanical energy is dissipated after the steady state has been established. It can vanish everywhere only if there is no dissipation of energy at all; the body can then have no other motions than a general rotation with constant angular velocity, although for the simple case of constant μ we can, in addition, have a uniform contraction or expansion.

We shall now vary the velocity of an element of the fluid and the path it describes under the influence of inertia, gravity, pressure gradients, and viscous forces, first studying the case in which the proper co-ordinate system is an inertial frame.

From the definition of T, u, v, and w, we find

$$\Delta T=\tfrac{1}{2}\Delta(u^2+v^2+w^2)=u\Delta\left(\frac{Dx}{Dt}\right)+v\Delta\left(\frac{Dy}{Dt}\right)+w\Delta\left(\frac{Dz}{Dt}\right)$$
$$=u\frac{D}{Dt}(\Delta x)+v\frac{D}{Dt}(\Delta y)+w\frac{D}{Dt}(\Delta z)=\frac{D}{Dt}(u\Delta x+v\Delta y+w\Delta z)$$
$$-\left(\frac{Du}{Dt}\Delta x+\frac{Dv}{Dt}\Delta y+\frac{Dw}{Dt}\Delta z\right).$$

Hence

$$\int_{t_1}^{t_2}\left(\Delta T+\frac{Du}{Dt}\Delta x+\frac{Dv}{Dt}\Delta y+\frac{Dw}{Dt}\Delta z\right)dt=[u\Delta x+v\Delta y+w\Delta z]_{t_1}^{t_2}. \qquad (7)$$

At the fixed times t_1 and t_2 the variations Δx, Δy, and Δz are supposed to vanish, and the integral must hence be equal to zero.

Multiplying equations (2), respectively, by Δx, Δy, and Δz, adding, and using equation (7), we obtain

$$\int_{t_1}^{t_2}(\Delta T-\Delta G+f_x\Delta x+f_y\Delta y+f_z\Delta z)dt=0\,. \qquad (8)$$

According to our assumptions both G and T can be regarded as continuous, finite, and single-valued functions of x, y, and z, con-

taining terms changing slowly with time. We can then replace T and G by their mean values. We write

$$T=T_m+(t-t_m)\frac{\partial T}{\partial t},$$

$$G=G_m+(t-t_m)\frac{\partial G}{\partial t},$$

where $t_m=(t_1+t_2)/2$, and T_m and G_m indicate average values of the kinetic and gravitational energies, reduced to unit mass.

T and G may depend explicitly on the time, however, without affecting our conclusions. The important thing is that we limit ourselves to the cases in which the motions become more and more steady, so that we can regard T, when referred to a proper co-ordinate system, as being a function of x, y, z, and t, and not of the velocity, as in the usual Lagrangian equations.

Equation (8) can now be written in the form

$$\Delta\int_{t_1}^{t_2}(T-G+xf_x+yf_y+zf_z)dt=0, \tag{9}$$

where Δ indicates a space variation, and where f_x, f_y, and f_z are not varied. Equation (9) can be regarded as a condition for a minimum of "action" of the "kinetic potential" $(T-G)$, the viscous forces, and the pressure gradients, all reduced to unit mass.

The partial space derivatives of (9) must vanish; and, since t_1 and t_2 are arbitrary quantities, the integrands themselves must vanish. Hence

$$\left.\begin{aligned}\frac{\partial(T-G)}{\partial x}+f_x&=0,\\ \frac{\partial(T-G)}{\partial y}+f_y&=0,\\ \frac{\partial(T-G)}{\partial z}+f_z&=0.\end{aligned}\right\} \tag{10}$$

Multiplying (10) by u, v, and w, respectively, we find, using (2) and (3),

$$\frac{D}{Dt}(T-G)=-(f_x u+f_y v+f_z w)=-\frac{A}{\rho}=\varphi\,. \tag{11}$$

From (6) and (11),

$$\frac{DT}{Dt}=0\,, \tag{12}$$

$$\frac{DG}{Dt}=-\varphi\,. \tag{13}$$

In interpreting equations (12) and (13) we must remember several things. We have assumed $\partial T/\partial t$ and $\partial G/\partial t$ to be small compared to

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}$$

and to

$$u\frac{\partial G}{\partial x}+v\frac{\partial G}{\partial y}+w\frac{\partial G}{\partial z}\,,$$

respectively; hence the equations are valid only when the variations in velocity and gravity at any one fixed point are slow. Second, the usual conception of the "velocity following an element of the fluid in its motion" has in our case a statistical meaning only, since we have no means of identifying a "fluid element" in its motion. Consequently, we cannot say anything about what happens when we "follow" an element during an indefinite time. We can only say that at any time the instantaneous velocity vector lies in a surface of constant scalar velocity (equation 12). The gravitational energy decreases as we follow the local movements (equation 13); hence the instantaneous velocity vector cuts the surfaces of constant gravitational potential inward. The surfaces of constant scalar velocity and constant gravitational potential are both supposed to form a set of closed, non-intersecting surfaces. Since the motions are systematically inward, the system contracts, and the surfaces of constant T

and G are slowly changing. In the limiting case when $\varphi = 0$, there is no longer any contraction, and the system has dissolved itself into a single star or a group of stars, all rotating as solids.

The loss in gravitational energy is equal to the gain in heat and pressure energy; none is converted into kinetic energy after the steady state has been established. On account of the rise in temperature, the energy carried away at the surface by escaping particles may be very considerable. We thus see that viscous forces produce at the same time a scattering and a condensation; we confine our study to the contracting system.

It is interesting to note the rapid changes in the moment of inertia of the system. We write the virial theorem in the form

$$\frac{1}{2}\frac{D^2I}{Dt^2} = \int (2T+G)dm ,$$

where I is the moment of inertia. Differentiating with regard to time, we obtain

$$\frac{1}{2}\frac{D^3I}{Dt^3} = \int \left(2\frac{DT}{Dt}+\frac{DG}{Dt}\right)dm .$$

Hence, from (12) and (13),

$$\frac{D^3I}{Dt^3} = -2\int \varphi \, dm = -2\Phi . \tag{14}$$

Φ is the dissipation function, which is always positive when there is internal motion in the system. Dealing, as we are, with the third time-derivative, it is clear that the moment of inertia must decrease rapidly when Φ is finite. Since particles escape at the surface, the decrease is still more rapid than equation (14) indicates.

Since the particles we are considering are built up of electric charges, the shake-up of the particles themselves by collisions produces, in general, radiation, which may be released immediately, or later when atomic readjustments take place. Ionization may also take place, resulting in the liberation of electrons. In a particular element of the fluid, we have then several forms of energy, parts of which are retained in the element, while other parts are transferred to adjacent elements or to the surrounding space. We shall still as-

sume, however, that an approximately steady state of motion like the one previously considered will gradually be established.

Under this condition we find that, if there is no source of energy in the interior, $\int\int\int C dxdydz$ is negative. B now includes the rate at which microscopic forms of energy in general are produced. Since C is predominantly negative, $\varphi = (B-C)/\rho$ is still positive and numerically larger even than in the case previously considered. We can still regard the average values of T and G as functions of position, and equations (11), (12), and (13) still hold.

The quantity φ is the rate at which mechanical energy per unit mass is dissipated. The difference between the case in which radiation is produced and lost to the surrounding space and that in which no radiation is lost lies in the resultant distribution of temperature, density, and pressure, and in the greater speed at which the contraction proceeds in the first case, as compared with the second. For the first, φ is positive even after B has reached a zero value, and contraction can hence proceed after rotation as a solid has been reached —a fact utilized in Laplace' theory.

NEBULA WITH AXIAL SYMMETRY

Let us now apply these results to the development of a nebula in which the density decreases from a center outward in a more or less regular fashion. Before a steady state is reached, a general contraction occurs owing to the escape of particles of high velocity and to the loss of energy by radiation produced by the collisions. The velocities in the central part increase gradually, and so also do the density, temperature, and pressure.

If the density distribution is such that in the first approximation it has axial symmetry and the density decreases outward from a single center, viscosity will produce motions which, referred to an inertial reference-frame fixed to the center, will ultimately be approximately steady. After this state is established, the velocity of a moving "element" remains constant (like that of a body freely falling in a viscous fluid) and every element has an "inward" velocity component. At any particular point in the fluid the velocity will, however, change with time. For the simple case considered, in which no very large secondary condensations are produced, the

system at any single instant will have a shape and a density distribution symmetrical about an axis of rotation coinciding in direction with the original total angular-momentum vector. There will also be a plane of symmetry perpendicular to the axis of rotation. It is also clear that surfaces of equal pressure, temperature, viscosity, gravity, and scalar velocity will all be symmetrical about the axis of rotation and about the equatorial plane.

If the density gradient is not exactly uniform, the general tendency toward contraction must also show as a tendency toward local condensation. Before the steady state is reached, local condensations may form and be dissolved; but after this state has been attained, such condensations no longer dissolve but tend to increase in density and mass, provided the secondary condensations are so small that the disruptive effects of tidal forces can be neglected. The theory can hence be applied to the formation of stars, but caution must be used when applying it to very extended stellar groups. As long as the density around the condensations is everywhere still finite, the motion of an element of the fluid is affected by the viscous forces and the pressure gradients. During the gradual accretion of the condensation, the atmosphere around it receives a net outward momentum corresponding to the decrease in the pressure gradient. When ultimately the density outside the condensation vanishes and the viscous forces and the pressure disappear outside the condensations, equations (12) and (13) are still valid, with a value of φ outside the condensation equal to zero, provided free particle motion can take place along surfaces of constant gravitational energy. Since condensations formed outside the central plane will *gradually* sink into this plane, the final orbits will all lie in this common plane of motion. For a density distribution symmetrical about an axis, the final orbits of stars developed from the gas are, hence, circles in a common plane perpendicular to the axis of symmetry.

The angular velocity ζ at a distance r from the axis of symmetry is given by the equation

$$2\zeta=\frac{dv_2}{dr}+\frac{v_2}{r}, \tag{15}$$

where v_2 is the velocity perpendicular to the radius vector. For the limiting case ζ equal to zero, $v_2=c/r$, which represents the usual con-

ditions of motion about a straight vortex core when the fluid is kept immovable at "infinity." But in the present case there are no forces acting on the "boundary" of the system, the velocities are not zero at the "boundary," and the rate at which v_2 decreases with r is less than in the usual case. Putting, approximately, $v_2 = c/r^n$, we have in general $n < 1$, with the result that ζ is everywhere positive—that is, the local rotation is everywhere in the same direction as the general rotation. The exponent n decreases with the time, since in the other limiting case, namely, that of a motion as a solid, we have $n = -1$.

If a star is formed before the steady state has been established, it may have any rotation. It may also have a velocity differing greatly from circular motion; and it may have a velocity component perpendicular to the plane of symmetry. The bodies so formed, as explained in *Contribution* No. 492, are the high-velocity stars in the galaxy and the asteroids in the solar system. The steady state may never be completely established, but may, nevertheless, serve as a useful standard indicating a general tendency.

It is important to note that the rate at which viscous forces can reduce space gradients in the angular velocity depends upon the density and the dispersion in velocity of the particles, that is, upon the "temperature" of the gas, and also upon the mean free path and the dimensions of the system. When the condensations which later become stars are formed, the nebula is supposed to be *many times greater* than after the stars are developed; further, the temperature is supposed to be very low. The low temperature, coupled with the very small density of the system, makes the rate at which viscous forces can reduce the velocity gradient very small, in spite of the long free path. It is not surprising, therefore, that the nebulae do not rotate as solids. The same conclusion applies to the gas forming the solar system. According to the present picture, the dimensions of this system were originally of about the same order as interstellar distances, and the planets were not formed *in situ* but at much greater distances from the sun than they are now.

It is very probable that condensations with masses much smaller than those of stars or planets are first formed, and that these condensations later combine into stars, planets, or satellites. If this is so, the condensations will tend to sink into the central plane and the

system will become very much more flattened than would be the case when no small condensations are formed. The small condensations may well be identical with the "planetesimals" of Moulton and Chamberlin. A great number of these condensations have not yet combined with larger bodies; they still exist and are often seen individually as meteors and in groups as comets or showers of meteors. Whether the bodies finally formed will have masses equal to those of the particles in Saturn's ring, or of the order of those of satellites, planets, or stars, cannot be predicted. This detail depends upon the degree of regularity in the original distribution of density and temperature and the extent of the regions of uniform motion at the time these bodies were formed.

TWO CONDENSATION CENTERS

The case involving two condensation centers with masses of the same order of magnitude can also be studied, provided their relative motion is nearly circular. As long as there is still intervening gas, gravitational energy is dissipated and the system contracts. A time will come, however, when the two condensations can be regarded as separate bodies, which still contract although their mutual distance no longer systematically decreases. If a small condensation has been formed slowly and has gradually sunk into the equatorial plane, it will also move, at least approximately, in the common plane of motion. We introduce a co-ordinate system rotating with the constant angular velocity ω of the two large condensations, the origin being at the center of mass of the system. Denoting co-ordinates and velocities referred to the rotating system with subscripts, we find as before:

$$\left.\begin{aligned} &\frac{DT_1}{Dt}=0\,; \qquad \frac{D}{Dt}\left(G-\frac{\omega^2 r^2}{2}\right)=-\varphi\leq 0 \\ &2T_1=u_1^2+v_1^2+w_1^2\,, \qquad r^2=x_1^2+y_1^2=x^2+y^2\,. \end{aligned}\right\} \tag{16}$$

These equations determine the changes in the kinetic and gravitational energies of an element of the gas, reduced to unit mass. The velocity vector always lies on a surface of constant scalar velocity. The surfaces $G-\omega^2 r^2/2=\text{const.}$ are analogous to the surfaces of "zero

relative velocity" in the restricted problem of three bodies. It has been shown by Miss Rein[10] that the structure of these surfaces, when the bodies are surrounded by an attracting mass of gas or dust, is completely analogous to Hill's surfaces. We can say that the motions are such that at a particular instant they nearly follow surfaces defined by the equation $G-\omega^2r^2/2=\text{const.}$, that these surfaces contract, and that the scalar velocity along any one of these surfaces is constant. In the end, all three bodies rotate in the same direction as the system, and the two massive bodies move in fixed circles about one another. The "satellite," however, cannot in general move along a surface $G-\omega^2r^2/2=\text{const.}$, since it has now a free-particle motion, and the only periodic orbits inclosing one of the attracting centers are of another type. Motions along the foregoing surfaces are possible only so long as viscous forces and pressure gradients are still acting. Close to the planet, however, where the perturbations are small, we may have free-particle motions in direct, nearly circular orbits, with no secular changes in the size of the orbit —a well-known theorem in the theory of perturbations. Farther out, a satellite moving freely in a direct orbit would be so greatly disturbed by the sun that it would sooner or later come very close to its primary and be involved in the gaseous envelope and probably drawn in or disrupted. If it moved in a retrograde orbit closely resembling one of the known periodic orbits, it could keep on moving without ever coming too close to its primary. If the orbit were retrograde in the non-rotating system, such a satellite could not have been formed after the steady state described had been established, since the motions in the layer between direct and retrograde motion do not represent minimum action. It would either have been formed before a steady state was reached or have been captured by the aid of frictional forces in the gas surrounding the primary. But these forces must be so adjusted that they would take away just enough kinetic energy from the satellite to make the orbit nearly periodic. Since so fine an adjustment is improbable—just as circular motions are improbable without the aid of viscous forces—and since several retrograde outer satellites exist, it seems possible that a locally stable

[10] "On the Masses of Condensations in Dust Nebulae," *Astron. Jour. Soviet Union*, 10, 4, 1933.

state of fluid motion exists, corresponding to retrograde motion along surfaces of zero relative velocity. For a limited region we can then also regard the velocity as a continuous, single-valued function of position.

Nothing is known about periodic orbits with high inclinations to the plane of motion of the attracting centers. Hence we cannot say anything about the formation of the satellites of Uranus and Neptune, except that motions parallel to the ecliptic had not yet been established when the satellites were formed.

ROTATION PERIODS IN THE SYSTEM OF SATURN

The present theory may account for the peculiar fact that the inner ring of Saturn has a shorter time of rotation than the surface of the planet. The difficulty of explaining this fact from the standpoint of Laplace' theory has been emphasized by Moulton.[11] In the present picture, when Saturn was greater than at present, its internal motion deviated much more from that of a solid than it does now. It was also surrounded by a flat disk of gas in the equatorial plane before the solid particles in the ring had completely condensed. During the condensation process an outward gas pressure was active, and its disappearance was accompanied by an increase in the circular motion of the ring, which must be retained, according to equations (12) and (13), even though the pressure gradually disappears. The circular velocity must hence increase until free-particle motion is established. This conclusion does not contradict equation (12), since the matter in the "element" whose motion we are following is contained partly in the condensation and partly in the surrounding gas.

On the surface of the planet when still in a gaseous state, we did not have free-particle motion, but a balance between gravitational forces on the one hand and centrifugal forces and pressure gradients on the other. In the present theory the angular momentum is not conserved, since the escape of particles in the atmosphere carries away a large part of this momentum. When the surface has become more or less solidified, we may well have a velocity at the surface considerably smaller than the free circular motion, as is now the case on the earth.

[11] *Ap. J.*, **11**, 111, 1900.

CHANGES IN MOTION AFTER THE FORMATION OF THE STARS

The present study forms a complement to the valuable work of Bok[12] about the stability of moving star clusters. He has shown that such clusters tend to disperse, owing to the effect of tidal forces from an attracting central mass in the galaxy. The theory here outlined shows that previous to the formation of the stars and the stellar groups we have a general tendency toward concentration of matter into stars moving in nearly parallel, circular orbits about the center of the galaxy. Bok's theory hence refers to the later changes in the motions of the stars after their formation.

FORMATION OF HEAVY ATOMS AND OF PLANETS

An interesting phase of the present theory may be mentioned here. We are inclined to think that heavy atoms are formed from hydrogen, neutrons, and electrons in the hot interior of the stars. The matter in the earth and the planets is supposed to have been ejected by the sun after the heavier atoms were formed. But in the present picture the matter in the earth was never in the melting-pot of the sun or of any other star after the steady state of motion had been established. But perhaps heavy atoms existed in the primordial gas, or were formed by processes not requiring excessive heat; or the sun may have exploded like a nova long ago, and what we have been studying are the processes following this cataclysm. We have some evidence that nova outbursts are normal phenomena among the stars.

If we admit that heavy atoms can be formed only in the interior of stars, the matter of which the planets are built up must have been ejected by the sun, either as a nova outburst or as a consequence of a close encounter with another star. In the first case, planetary systems like that of the sun are very common. In the second case, they are extremely rare phenomena in the universe. In whatever way the cataclysm happened, it does not affect the present picture of development, which deals only with changes occurring after a steady state of motion was last established.

CARNEGIE INSTITUTION OF WASHINGTON
MOUNT WILSON OBSERVATORY
August 1934

[12] *Harvard Circ.*, No. 384, 1934.

SPECTROPHOTOMETRY OF RS OPHIUCHI (NOVA OPHIUCHI NO. 3)*

By O. C. WILSON and E. G. WILLIAMS[1]

ABSTRACT

From one good plate taken with the three-prism violet spectrograph on August 30, 1933, the apparent color temperature of RS Ophiuchi is found to be 4000° K.

Contours of the hydrogen emission bands have been determined from several plates covering the period August 16–September 11, 1933. On the assumption that the red sides of the bands present the true unmodified shapes, the following facts emerge:

a) The contours are roughly exponential in form. The earlier ones can be represented approximately by the formula $I = e^{-(u/u_0)^n}$, where $n = 1 + k(u_0/u) - k$ and $k = 0.125$. The value u_0 decreases rapidly with time at first, then more slowly, finally attaining a more or less constant value; k also decreases and may be considered to vanish for the later contours.

b) In addition to a sharp absorption component present on the short-wave-length sides of the band maxima in the early stages, there appears to be a general deficiency of intensity over the violet halves of the bands relative to that of the red halves. The supposition that this is due to the complete suppression of the continuous spectrum under the violet sides is not in entire agreement with the facts, but there may be complicating factors. This hypothesis would require a large velocity range among the atoms directly in front of the star, and leaves no room for the monochromatic hydrogen absorption components or for the sharp nebular lines. It is suggested that the latter arise in a quiescent shell around the star left over from its previous outburst.

The Balmer decrement has been obtained from two accordant plates, and is found to be appreciably faster than the mean of those found by Plaskett and by Berman for planetary and diffuse nebulae. The observed decrement is brought into good agreement with the latter by applying the differential factors necessary to reduce a true temperature of 35,000° to an apparent one of 4000°. From several spectrograms it appears that the ratio of the area of $H\gamma$ to the intensity in the underlying continuous spectrum did not vary greatly between August 16 and September 2, 1933.

Zanstra's method gives a photo-electric temperature of 35,000°, calculated from the measures on plate V404, August 18. If this is a real measure of the temperature, it follows from the preceding paragraph that, while the star decreased in brightness by about two magnitudes from August 16 to September 2, its temperature remained constant. This conclusion would imply that the fading of the star was due to a shrinkage in the radiating surface.

From the measured intensity of the K line, with an approximate allowance for a probable stellar blend, a distance of 950 parsecs is deduced. This is shown to be fairly consistent with the recent results of Stebbins and Huffer on the assumption that the difference between the photo-electric and apparent temperatures is due to space reddening.

I. APPARENT COLOR TEMPERATURE

RS Ophiuchi has been classed as a nova since 1901, when it was discovered at Harvard that in 1898 the star increased to magnitude

* *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington*, No. 501.

[1] Fellow in Astronomy on the Commonwealth Fund.

7.7 from a normal brightness of around 11. Between 1898 and 1933, aside from a smaller maximum of about the ninth magnitude in 1900, the star appears to have undergone only minor fluctuations in brightness around its previous normal value. On August 15, 1933, Peltier announced a sudden increase to magnitude 6.4. Later reports indicate that the maximum occurred on August 12 at 4.3.[2]

During several months following the maximum a number of spectrograms were obtained by various observers at Mount Wilson. Among them were two, V404 and V405, taken with the three-prism violet spectrograph by Wilson on August 18 and 30, and intended primarily for spectrophotometric analysis. The spectrograph used can be rotated about the optic axis of the collimator; and since the star is south of the equator and the observations were made near the meridian, the slit was set in the N-S line in order to minimize the effect of atmospheric dispersion.

The spectrograms were made on Imperial Eclipse Soft plates with a 10-inch camera giving a dispersion of 38 A/mm at $H\gamma$. Photometric standards consisting of ten continuous spectra of known ratios were impressed on the plate during the star exposure by means of an arrangement built into the spectrograph. At the conclusion of the exposure on the nova, several spectra of α Cygni, then at a small zenith distance, were also recorded on the same plate.

Figure 1*a* shows a microphotometer tracing of plate V404 on which the spectrum was widened by running the star back and forth along the slit. The emission bands are well exposed, but the underlying continuous spectrum is rather weak for accurate measurement over a long range. On V405 the star was held stationary, and the centers of the stronger bands are burned out. The continuous spectrum, however, is suitable for measurement from about 5000 A to beyond $H\epsilon$. Our color-temperature determination therefore rests entirely on this one spectrogram.

The method employed in deducing the color temperature is that developed by the Greenwich observers.[3] Differences in intensity, expressed in magnitudes, between the continuous spectrum of the nova

[2] *Harvard Announcement Card*, No. 279. Observation of E. Loreta.

[3] Fully explained in *Observations of the Colour Temperatures of Stars Made at the Royal Observatory*, Greenwich (1932). In the subsequent calculations we have adopted the recently revised value, $\phi_0 = 1.0$, for the standard A0 star, as given in *M.N.*, **94**, 488, 1934.

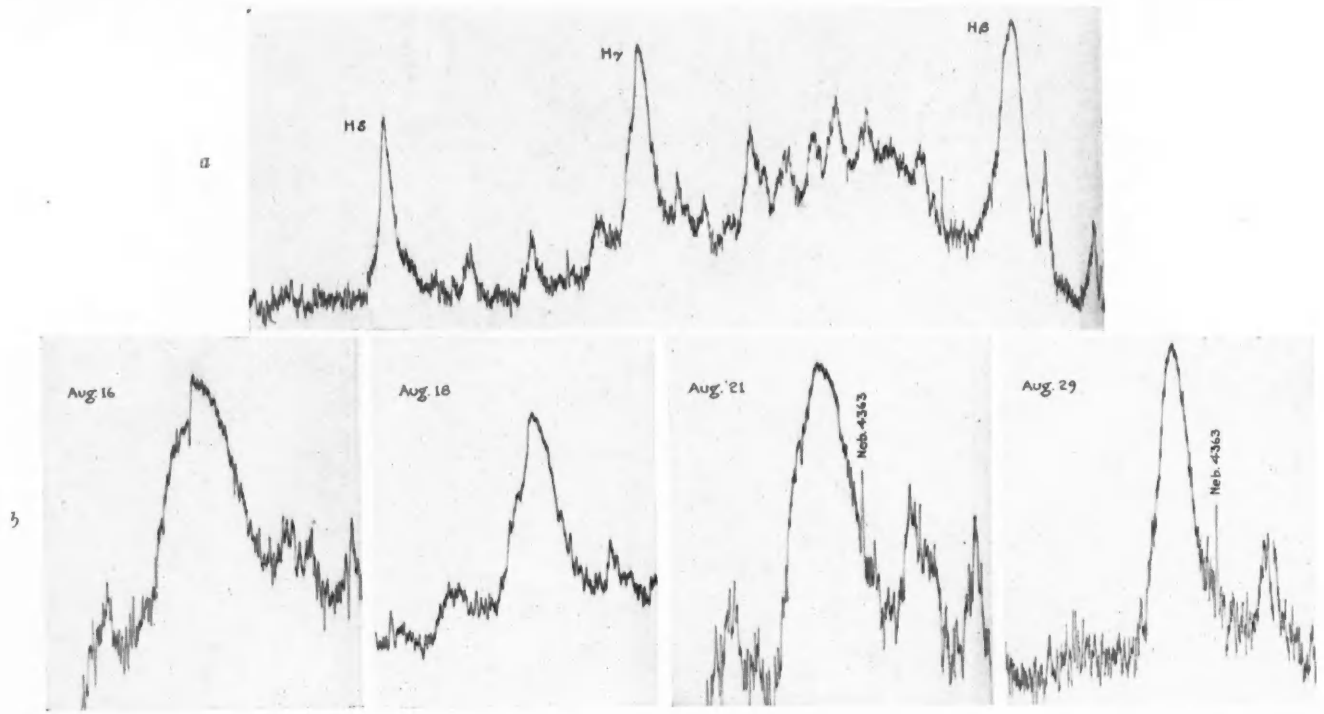

FIG. 1.—Microphotometer tracings of RS Ophiuchi: (*a*) August 18, 1934; (*b*) qualitative sequence of changes in $H\gamma$

and that of α Cygni are plotted against the reciprocals of the corresponding wave-lengths. For spectra of the black-body type, the plotted points should lie on a straight line. The observations are represented by the crosses in Figure 2. The upper solid line drawn through the observed points is transformed into the lower one by applying corrections for differential atmospheric extinction and for angle between the atmospheric spectrum and the slit, the latter computed on the assumption that the $H\alpha$ image was kept on the slit dur-

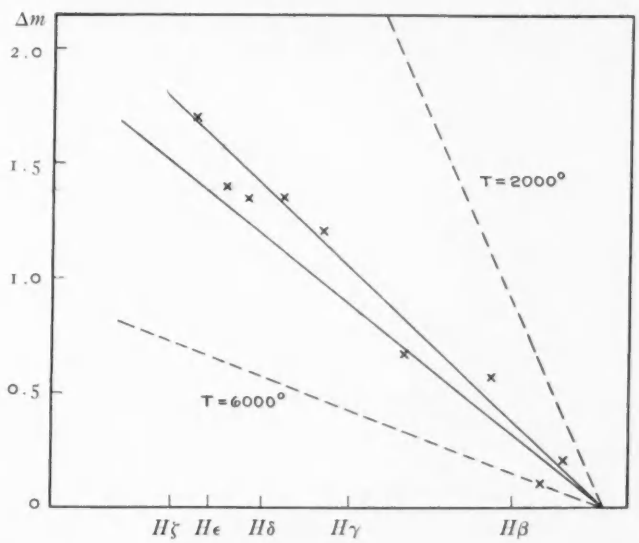

FIG. 2.—Color temperature of RS Ophiuchi. Abscissae, $1/\lambda$; ordinates, magnitude differences.

ing the exposure. This supposition is probably nearly correct, since the star, as seen in the telescope, was very red. In any event, the effect of the total correction is small.

The main uncertainty, and the probable source of most of the scatter in the observed points, lies in the difficulty of drawing in the continuous background on the tracing. The spectrum can best be characterized as "lumpy," and in some regions numerous emission bands overlap and undoubtedly produce an apparent continuous background which is considerably too high. This effect is especially conspicuous between $H\beta$ and $H\gamma$ and was allowed for as far as possible.

Using the slope of the lower solid line of Figure 2, we find $\phi_{RS} - \phi_{\alpha\ Cyg.} = 2.17$. The choice of α Cygni as a comparison star was unfortunate, since the Greenwich observers have found its color temperature to be variable. Nevertheless, with +0.30 as a reasonable mean value of its gradient, corresponding to a temperature of 12,200°, we find $\phi_{RS} = 3.47$. This value gives 4140° or, in round numbers, 4000° K as the apparent color temperature of RS Ophiuchi on August 30, 1933.

Although this determination is not of high accuracy, it is undoubtedly of the right order, as may be seen from the dotted lines in Figure 2, corresponding to temperatures of 6000° and 2000° K. Unless some large and unsuspected systematic error is present in our work, the color temperature of the star probably lies between these limits.

Dr. Joel Stebbins has kindly communicated to us the results of a set of photo-electric color determinations made by him at the 100-inch telescope on August 16, giving an integrated color corresponding to spectral type gG3. This result includes the hydrogen emission bands; and when allowance is made for them, the indicated type becomes somewhat earlier. Although Stebbins' result is not in very close agreement with ours of two weeks later, it at least confirms the moderately low color temperature found for RS Ophiuchi.

II. CONTOURS OF HYDROGEN EMISSION BANDS

Contour measurements of nova emission bands are by no means numerous.[4, 5] Fortunately, several spectrograms besides the two already noted are available for this purpose. These plates are one-prism spectrograms taken at Mount Wilson and photometrically calibrated by means of a tube sensitometer. Their dispersions are of the same order as that given by the three-prism violet spectrograph. The measures were made as usual by carefully sketching in the assumed continuous background below the band and using it as the zero point for the band emission intensities. Here again the presence of other emission bands affects the location of the background and introduces uncertainties into the measures of the hydrogen bands themselves, particularly in the wings. Nevertheless, the results, on the whole, seem to be satisfactory.

[4] C. S. Beals, *Pub. Dom. Ap. Obs.*, **6**, 115, 1934. [5] J. Genard, *M.N.*, **92**, 396, 1932.

Figure 1*b* shows several microphotometer tracings of $H\gamma$, illustrating qualitatively the course of events. $H\beta$ and $H\delta$ are, of course, similar to $H\gamma$ on each spectrogram. On the earlier plates the bands are asymmetrical. A sharp absorption line appears to the violet of the band center, and the intensity over the violet side as a whole is perhaps deficient as compared with the red. Later on, the sharp absorption component fades out and the asymmetry, while still present, becomes less marked. The bands then gradually approach symmetry

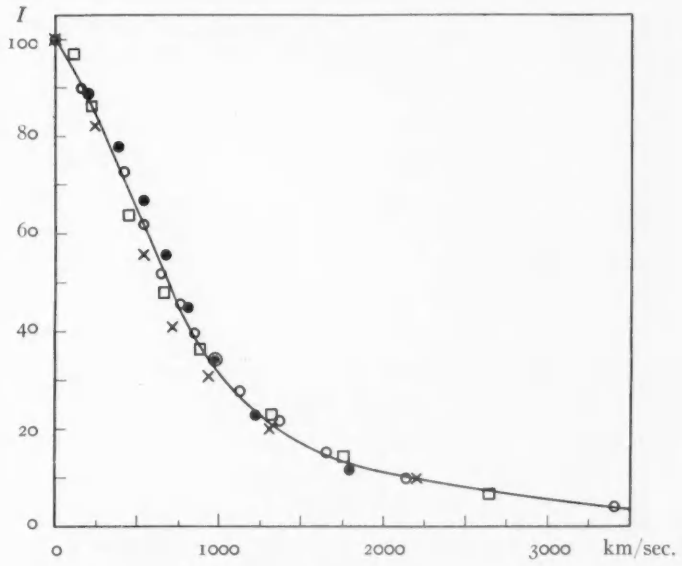

FIG. 3.—Hydrogen emission contours (red halves), August 16, 1934. Circles represent $H\beta$; dots, $H\gamma$; crosses, $H\delta$; squares, computed.

and decrease considerably in width. These matters will now be discussed more precisely.

Owing to the fact that, on the earlier plates, the violet halves of the bands are affected by absorption, we restrict ourselves for the moment to the red sides. The first question is the relation between band width and wave-length. The contours of the red sides of the bands on plate γ19820, taken on August 16, are plotted in Figure 3, the maximum intensity of each band being set equal to 100 and the widths expressed as velocities. The agreement between the three

bands is very good, and, in particular, there is no evidence of a progressive change in the order β, γ, δ. On this plate the maximum intensities of all the bands could be measured; but on γ19818, taken the same night, $H\beta$ was too intense at the center for measurement. The values for the outer portions of $H\beta$ can, however, be fitted very nicely onto the contours given by $H\gamma$ and $H\delta$; and, when this is done, the band shapes given by the two plates of August 16 agree perfectly. The contours of the red sides of the hydrogen emission bands in RS Ophiuchi on this date are therefore known with considerable accuracy.

Previous measures of nova band widths have been made by setting a micrometer wire as accurately as possible on the edges. Even at best, when the bands terminate sharply, there is some difficulty in knowing just what defines the "edge." This difficulty is enhanced by the considerable intensity gradient between successive bands and by psychological factors which probably vitiate the comparison of widths. Nevertheless, on the whole, the results indicate that band widths are proportional to wave-length.[6]

In the present instance the word "width" has little meaning in the foregoing sense, owing to the gradual tailing-off of the bands. But the evidence presented in Figure 3, which is typical of all our measures, shows that here, too, the structure of the bands is such that displacements are proportional to wave-length. This result is in keeping with, but does not necessarily establish, the hypothesis that the displacements are the result of radial motion.

The theoretical shapes of emission bands produced by expanding gaseous shells have lately been under investigation,[4, 7, 8] so it is undoubtedly worth while to see what kind of expression will represent those of Figure 3. The forms shown immediately suggest some sort of exponential. Experimentation with the equation $I = e^{-(u/u_0)^n}$ shows that it cannot be made to fit unless n is a function of u and that with

$$n = 1 + k\frac{u_0}{u} - k$$

[6] F. J. M. Stratton, article on novae, *Handbuch d. Astrophys.*, **6**, 1928.

[7] B. P. Gerasomivič, *Zs. f. Ap.*, **7**, 335, 1933.

[8] S. Chandrasekhar, *M.N.*, **94**, 522, 1934.

an acceptable approximation is obtained. The squares in Figure 3 were computed in this way, with $k=0.125$. The value u_0 is of course the velocity for which the intensity is $1/e$ of its maximum value.

Chandrasekhar, whose results include those of Gerasimovič, has published drawings of the contours to be expected if certain assumptions are fulfilled. None of these curves resemble, even remotely, our observed contours. Since we believe the observational results to be

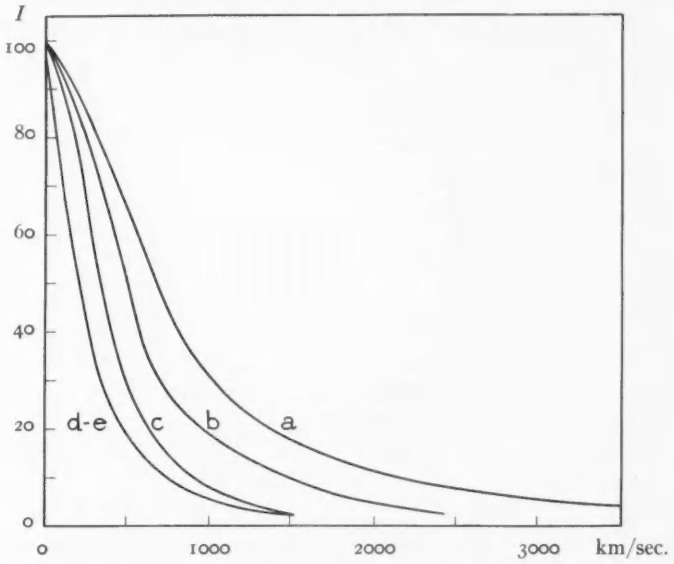

FIG. 4.—Mean contours of red sides of hydrogen emission bands: (*a*) August 16; (*b*) August 18; (*c*) August 30; (*d–e*) September 2, 11, 1933.

fairly reliable, we conclude that for some reason the theory, as thus far developed, does not apply to RS Ophiuchi.

We have also determined the contours on several other plates covering the entire interval from August 16 to September 11. On some of these spectrograms the central region of $H\beta$ was overexposed, but experience with the two plates of August 16 indicates that the $H\beta$ measures may be satisfactorily fitted onto those of the other bands. The results are shown best by plotting the mean shapes, as in Figure 4, the essential data for which are in Table I. For the plates following V404 the bands are so nearly symmetrical that half of the total width has been used in plotting.

The contours of September 2 and 11 coincide so closely that they cannot be separated on the scale of the drawing. Moreover, they are of the simple exponential type, i.e., $k=0$. It has not been considered important to derive the value of k for August 18 and 30, since it is evident that there is a continuous transition in the contours.

The decelerating rate of change of the band shapes is noteworthy. The decrease in width (u_0) from August 16 to 18 is 84 per cent of that during the twelve times longer interval August 18–September 11. Unfortunately, after September 11 it was possible to secure spectrograms of only rather small dispersion, but an inspection of plates of October 1 and 29 shows that on these dates $H\beta$ had approximately

TABLE I

Curve	Plate	Date	u_0	k
			km/sec.	
a	γ19818, γ19820	1933 Aug. 16	880	0.125
b	V404	Aug. 18	620	.....
c	V405	Aug. 30	440	.....
d	γ19837	Sept. 2	310	0.000
e	V435	Sept. 11	310	0.000

the same general appearance and width as on September 11. Thus it seems safe to say that the band widths decreased very rapidly for a time after maximum, the rate of decrease becoming gradually smaller until about September 1, and that for at least two months thereafter the changes in width, if any, were small.

The violet halves of the bands differ markedly from the red sides only on the plates of August 16 and 18. On plotting the violet contours derived from these spectrograms in the same way as for the red halves, one general fact emerges at once, namely, that, aside from the one point where the maxima of the three bands are made to coincide, the contour of $H\beta$ is everywhere higher than that of $H\gamma$, which, in turn, lies above that of $H\delta$. Two interpretations are possible. Either, for a given intensity, the bands are successively narrower in the order β, γ, δ, or, for a given width, they are successively weaker in the same order. The second alternative appears more like-

ly in view of the good agreement found between the shapes of the red sides of the bands, on the reasonable supposition that the physical cause of the widening is the same in both cases.

If we are to adopt the second point of view, the increasing deficiency of intensity, in proceeding down the series, of the violet relative to the red portions of the bands must be accounted for. The appearance of the sharp absorption components on the bright bands suggests strongly that they are a true absorption phenomenon. If we now suppose, in addition, a general absorption effective over the entire violet sides of the bands, sufficient in amount to suppress more or less completely the light from the star's continuous spectrum in those frequencies, the result would be qualitatively similar to that observed. The reason for this conclusion is that the emission intensities in the bands decrease much more rapidly from β to δ than do the corresponding intensities in the continuous spectrum. Hence, if the sections of the continuous spectrum under the violet halves of $H\beta$ and $H\delta$ are removed by absorption, a greater relative difference between the two halves of the band will be introduced in the latter case than in the former.

TABLE II

Band	(*a*) Red Half	(*b*) Violet Half	(*c*) Reduced Red
$H\beta$	1.00	1.00	1.00
$H\gamma$	0.51	0.28	0.46
$H\delta$	0.10	0.04	0.07

It is possible to make a rough test of the validity of this hypothesis in the following way. The red and the violet halves of the bands on the two plates of August 16 were plotted separately on a true intensity scale, and the areas under them determined with a planimeter. The measured intensity in the continuous background under each band was then subtracted from the contour of the red side, yielding, what we may call for short, the reduced red contour. The reduced contours were sketched in, leaving the peak intensities unchanged. The mean relative areas resulting from this procedure, with β taken as unity in each case, are given in Table II.

If the difference between the red and the violet halves of the bands were due entirely to the suppression of the continuous spectrum under the latter, columns (*b*) and (*c*) of Table II should be identical. This should be true, moreover, whether or not the unmodified shapes of the two sides of the bands were the same. It is also to be noted that the discrepancy between (*b*) and (*c*) will be increased if it is supposed that only a part of the continuous spectrum below the violet sides is missing.

There seems to be no way of extending this argument. The measures of the August 16 plates agree in showing that, below the sharp discontinuity, the violet side of $H\beta$ is wider and has a greater area than the red half. This in itself would break down the absorption explanation if the bands were intrinsically symmetrical. The widths and areas of the violet sides of $H\gamma$ and $H\delta$ do not present this difficulty, however, and the close agreement between the values of $H\gamma:H\delta$ in columns (*b*) and (*c*) is to be noted. It is quite possible that blends interfere with the violet wing of $H\beta$, although there is no direct evidence of their presence.

In spite of all these uncertainties, we cannot escape the feeling that at least part of the asymmetry in the bands is produced by absorption in the manner presented above. If so, we must conclude that the velocity range of the absorbing atoms in the direct line of sight to the star is of the same order as the band half-width. In fact, if the bands are intrinsically symmetrical, the measures show that the underlying continuous spectrum may be completely removed out to a displacement from the band center corresponding to a velocity of the order of 2000 km/sec. without producing a depression in the apparent continuous spectrum on the tracing. This circumstance would be in good agreement with the fact that the observed contours are so widely different from the theoretical, flat-topped, square-sided ones to be expected from an expanding shell of atoms with no internal velocity range. To account for the necessary accumulation of atoms in the lower level of the Balmer series, the metastability of the $2S$ state of the hydrogen atom can possibly be invoked.

In conclusion, it is only proper to point out that this hypothesis leaves no room at all for the almost monochromatic absorption components of hydrogen or for the equally sharp bright nebular lines

(see Fig. 1*b*). These clearly originate in regions where the velocity range of the atoms is very small. Possibly the star was surrounded by an outlying quiescent shell of gas produced by its previous outburst. We would then suppose that when the radiation of the present outburst first arrived at this shell the excitation would be mild enough for a while to leave an appreciable fraction of the hydrogen atoms in the second (and perhaps other) levels. Then as the full effect of the burst of ultra-violet quanta made itself felt, the hydrogen would become completely ionized, the sharp absorption components would disappear, and their place would be taken in due time by the almost equally sharp nebular lines. If this was indeed the case, the radius of the outlying shell was probably of the order of several light-days.

Only one fact seems to emerge, with moderate probability, from this welter of supposition and that is that the complete explanation of all the observations in a case like the present one is likely to be fairly complicated. In fact, clear, unambiguous conclusions about these matters are, thus far, notable chiefly for their rarity.

For obvious reasons, it is greatly to be regretted that we could not include measures of $H\alpha$. Several plates of that region of the spectrum were available, but the band itself was invariably so badly overexposed, even when the continuous spectrum was very weak, that little or no reliance could be placed on the results. We have also determined on plate V404 the relative intensities of the bands in the 4500–4700 A region. The difficulty here was the impossibility of measuring wave-lengths with sufficient accuracy to be certain of the identifications in this notoriously blended mass of Fe^+, Ti^+, etc. Without proper identifications, the intensities by themselves are of little value.

III. THE BALMER DECREMENT

Probably one of the most important sources of information for deducing the nature of the physical processes occurring in novae will ultimately be measures of the relative intensities of the emission lines. In the present case our efforts in this direction have been restricted to a determination of a portion of the Balmer decrement. Plates V404 and V405, for which the necessary corrections can be found, have been used for this purpose.

On plate V404 the asymmetry of the bands is still noticeable, although not marked. Therefore the decrement from this spectrogram, obtained in the usual way by measuring the areas under the band contours, must be considered as a mean for the two sides of the bands. The central parts of both $H\beta$ and $H\gamma$ are overexposed on the plate of August 30, V405, so that the same method of determining the decrement could not be used. Since, in this case, the bands are quite symmetrical, the following procedure was adopted. The bands were plotted with the intensities on a logarithmic scale, and a mean contour representing all of them as accurately as possible was drawn on tracing paper. The vertical displacement necessary to bring each contour into agreement with the mean then gave the relative intensity at once. Finally, these apparent intensities were corrected for atmospheric absorption and for the angle between the atmospheric spectrum and the slit, and reduced to true relative intensities by making use of the standard α Cygni spectra on each plate. The results are given in Table III and are shown graphically in Figure 5, together with the mean of the results of Plaskett[9] and of Berman[10] for several planetary and diffuse nebulae. Except for $H\beta$, the ratios from the two plates are in excellent agreement. Owing to the fact that the bands are still somewhat asymmetrical on V404, a rather steeper decrement is to be expected from this plate than from V405. This effect may partly account for the discordance in $H\beta$, but probably the fact that the band is overexposed on the later plate is more to blame.

TABLE III

BALMER DECREMENT IN RS OPHIUCHI

Band	V404	V405	Band	V404	V405
$H\beta$	471	326	$H\epsilon$	20	19
$H\gamma$	100	100	$H\zeta$	.....	25
$H\delta$	39	40	$H\eta$	.....	(16)

$H\zeta$ is undoubtedly measured too intense because of blending with $He\ \lambda$ 3888.6. The value obtained for $H\eta$ is of low weight because of

[9] H. H. Plaskett, *Pub. Dom. Ap. Obs.*, **4**, 187, 1931.

[10] L. Berman, *Lick Obs. Bull.*, **15**, 97 and 102, 1930.

the extreme faintness of the image on the plate. We consider it likely, however, that this band is stronger than would be judged by an extrapolation of the straight line drawn through β, γ, δ, and ϵ. $H\epsilon$ also may be measured a little too strong because of $He\ \lambda\ 3964.7$.

In respect to Figure 5 it should be remarked that the horizontal scale is such that from an origin on the right (not on the diagram) the distances to the points marked β, γ, etc., are proportional to $n^{1/3}$, where, starting with β, $n = 2, 3$, etc. The vertical scale of intensities is logarithmic. This method of plotting is convenient, since it leads to linear relations for the observed quantities. The figure shows that

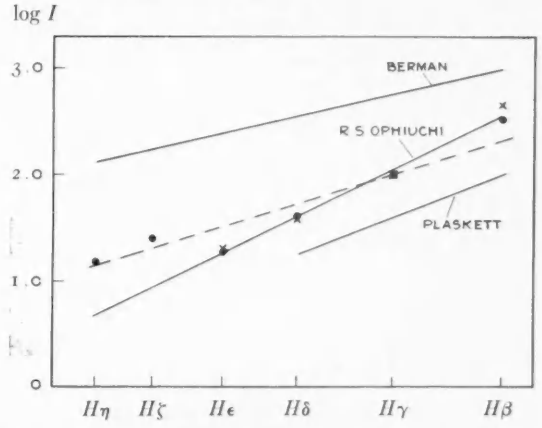

FIG. 5.—Balmer decrement; crosses represent V404; dots, V405

the observed decrement for RS Ophiuchi is appreciably faster than the nebular values of Plaskett and Berman. Several investigations[11, 12, 13] of emission-line B-type stars have shown that in these objects the decrement is very similar to that of the nebulae. The evidence thus far collected indicates, therefore, that throughout the considerable range of excitation extending from early B stars to planetary and diffuse nebulae the Balmer decrement shows little or no variation.

Let us assume for the moment that the intrinsic decrement in the present case is also the same as this more or less standard value.

[11] O. Struve, *Zs. f. Ap.*, **4**, 177, 1932.

[12] O. Mohler, *Pub. Obs. U. of Mich.*, **5**, No. 5, 1933.

[13] B. Karpov, *Lick Obs. Bull.*, **16**, 159, 1934.

How, then, is the greater observed steepness to be accounted for? Probably the most obvious explanation is selective absorption or scattering, due either to matter collected relatively close to the star or distributed more or less uniformly along the line of sight. In the next section we derive, by Zanstra's method, a photo-electric temperature for RS Ophiuchi of 35,000° K. If now we suppose that selective absorption or scattering is responsible for the change in apparent temperature from 35,000° to 4,000° K and apply the factors so derived to the observed Balmer decrement, we obtain the dotted line in Figure 5. Oddly enough, the slope of this line, which presumably represents the true decrement at the star, agrees remarkably well with the values of Berman and Plaskett, lying, in fact, between them.

TABLE IV

RATIO OF TOTAL INTENSITY OF $H\gamma$ TO INTENSITY OF CONTINUOUS SPECTRUM

Plate	Date	Ratio	Plate	Date	Ratio
19818	1933, Aug. 16	8.3	19824	1933, Aug. 29	11.3:
19820	16	10.4	V405	30	8.5
V404	18	7.4	V409	31	13.6
19823	21	7.9	19837	Sept. 2	9.0::

Of course this agreement may be entirely fortuitous; but it is, at any rate, suggestive. The ideal way to investigate the effect of space reddening would be to measure accurately the relative intensities of emission lines belonging to some multiplet extending over a fairly long interval of wave-length. If, then, on comparison with theoretical or laboratory ratios, the higher frequency members were found to be systematically too weak, the space-reddening point of view would be considerably strengthened. Unfortunately, the spectrum of RS Ophiuchi provided us with no unblended multiplets suitable for this test.

Collecting all our band-intensity material, we can answer one other important question, namely, what is the relation between the total emission in the bands and the intensity of the underlying continuous spectrum as the star fades? The data in Table IV are self-explanatory.

The available plates are of varying degrees of quality for photometric purposes; yet, as a whole, they show that, over the interval covered, the total emission in $H\gamma$ probably retained a constant ratio to the intensity of the continuous background at the same wavelength. Since the bands were becoming narrower during this interval, it follows that the continuous spectrum faded with respect to the peak intensities of the bands.

IV. THE PHOTO-ELECTRIC TEMPERATURE OF RS OPHIUCHI

The only mechanism thus far proposed for the production of bright hydrogen lines in nebular masses which permits a determination of the temperature of the exciting star is that due to Menzel[14] and to Zanstra.[15] Since the temperature computed by this method rests squarely on certain definite assumptions, we shall, in the present case, refer to it as "photo-electric" as a simple means of distinguishing it from other possible definitions of temperature. Zanstra's development and applications of this scheme are too well known to require more than the briefest résumé here. To arrive at the temperature of the central star in a planetary nebula, he makes the following main assumptions:

1. The hydrogen atoms in the nebula are ionized photo-electrically by ultra-violet radiation from the central star, and the bright lines are produced when protons and electrons recombine.

2. The star radiates as a black body.

3. The stellar radiation to the violet of the limit of the Lyman series is completely absorbed by the nebula.

4. The whole system is in a steady state.

Starting with this foundation, Zanstra shows that the temperature of the star is that value of T satisfying the equation

$$\int_{x_0}^{\infty} x^2(e^x-1)^{-1}dx=\sum_{\nu} x^3(e^x-1)^{-1}A_\nu\,,$$

where $x=h\nu/kT$, and x_0 is the value of x at the limit of the Lyman series. The observational quantities are the A_ν, defined[16] for a case

[14] D. H. Menzel, *Pub. A.S.P.*, **38**, 295, 1926.

[15] H. Zanstra, *Ap. J.*, **65**, 50, 1927; *Pub. Dom. Ap. Obs.*, **4**, 209, 1931.

[16] C. S. Beals, *M.N.*, **92**, 677, 1932.

like the present one, where the supposed nebular mass cannot be seen separately from the star, by

$$A_\nu = \frac{\int I_\lambda d\lambda}{\lambda I_s}.$$

The integrals are simply the areas under the band contours, and I_s is the intensity of the underlying continuous spectrum in the same units.

We have all the data needed to carry out a computation of this sort for our nova; the only question is one of justification. In the first place, assumption (4) is very definitely violated. RS Ophiuchi was in anything but a steady state during the time our plates were taken. Nevertheless, since it must be admitted at once that we are almost equally at sea as to whether any or all of the other assumptions are in accord with the facts, we may as well proceed on the hypothesis that the known failure of (4) is of no consequence. Since at best we can expect only order-of-magnitude accuracy, the use of one plate should suffice.

V404 was selected for this purpose, and the values of A_ν were computed from the measured intensities. To find A_α, it was assumed that $H\alpha$ would have had an apparent intensity six times that of $H\beta$. This figure was arrived at by extrapolating the straight line through the observed points of Figure 5. A_ϵ was added in twice to allow for higher members of the series. In passing, it may be noted that since Zanstra's method is not very sensitive, any reasonable assumption as to the intensity of $H\alpha$ would have led to nearly the same result. Zanstra's equation was then solved with the aid of his table for the integral, with the result $T = 35{,}000°$ K for the photo-electric temperature of RS Ophiuchi on August 18, 1933.

Whether this figure has any close correspondence with the true temperature of the star must, of course, depend on how nearly the assumptions underlying the computations agree with the facts. Presumably, if it has any meaning at all, it will be in the nature of a lower limit, as is generally the case with applications of Zanstra's scheme.

On the supposition that in this way we do obtain a measure of the star's temperature, one interesting conclusion may be drawn from the results presented at the end of the preceding section. It was shown there that the ratio of the area under $H\gamma$ to the intensity of the underlying continuous spectrum maintained a constant value from August 16 until September 2 at least. During this interval, therefore, the photo-electric temperature must also have remained constant. On the other hand, the apparent brightness of the star decreased during the same interval[17, 18] by about two magnitudes. Hence, if the photo-electric and true temperatures are comparable, or even run parallel, we conclude that the decreasing brightness of the star was due, not to a falling surface temperature, but to a shrinkage in the area of the radiating surface.

In this connection it is unfortunate that our material for the determination of apparent color temperature is limited to but one plate. A visual inspection of all available spectrograms leaves one, however, with the feeling that the intensity distribution in the continuous spectrum did not undergo any radical changes during the time covered by the observations. This conclusion is supported also by measurements of the relative intensities in the continuous spectrum at $H\beta$, $H\gamma$, and $H\delta$ on all available plates. While these ratios are necessarily of low weight, there is no indication of any progressive change with the time, a result in accord with the statements of the preceding paragraph.

The data presented here are reminiscent of one aspect of H. H. Plaskett's[19] study of Z Andromedae. It will be recalled that he found the apparent color temperature of this star to be almost certainly too low to provide the excitation demanded by the observed line spectrum. His measures of the Balmer decrement do not, however, give any support to the hypothesis that the low color temperature is a result of space reddening. If anything, he finds a slower decrement than usual.

[17] J. Rosenhagen, *A.N.*, **251**, 207, 1934.

[18] K. Bohlin, *ibid.*, **252**, 26, 1934.

[19] Plaskett, *op. cit.*, p. 119.

V. H AND K ABSORPTION LINES AND THE DISTANCE OF RS OPHIUCHI

The H and K lines of *Ca* II appear in absorption on several plates, but on only one, $\gamma 19819$, August 16, can they be measured photometrically. This is an excellent plate for the purpose, and we feel that the intensities obtained from it are entitled to some weight. H is superimposed on the broad emission of $H\epsilon$ but is well separated from its absorption component. K is also on an emission band of moderate strength, presumably that of *Ca* II in the star. If these lines were due entirely to interstellar calcium, some idea of the distance of RS Ophiuchi might be obtained directly from their intensities, but the measured radial velocities indicate that this may not be the case.

Merrill has constructed a diagram based on all available calcium and sodium velocities, from which we find that for a star having the galactic co-ordinates of RS Ophiuchi ($l = 348°$, $b = +8°$) a calcium velocity (including the component of the solar motion) of about -10 km/sec. might be expected. Since the star is located not far from one of the null points of the galactic rotation hypothesis, this velocity is practically independent of distance.

The mean velocity for the H and K lines (including one accordant measure of D_1 and D_2 of *Na*) derived from several plates by Adams and Joy is almost exactly -30 km/sec. The reason for the discrepancy may well be that the stellar H and K emission bands are accompanied by absorption components similar to those of hydrogen for which Adams and Joy find a velocity of -60 km/sec. If this is the true explanation, the observed H and K absorption lines are blends, about three-fifths being due to interstellar calcium and the remainder to the stellar components. In addition, it must be remembered that there may be an abnormal density of *Ca* II atoms around the star which originated in its previous outburst.

Williams[20] has recently published the results of a study of interstellar calcium line intensities in a number of B-type spectra. Using both H and K to arrive at the intensity of the latter as described in that work, and in the same units (wave-numbers) used there, we find: total absorption of K = 60. Assuming the blend explanation

[20] *Mt. W. Contr.*, No. 487; *Ap. J.*, **79**, 280, 1934.

for the anomalous velocity, we have 36 as the total absorption of the interstellar component.[21]

In order to use this result in estimating the distance of the nova, the K-line intensities of the above-mentioned paper were plotted against the distances of the stars given in the recent work of Stebbins and Huffer[22] on the colors of the B-type stars. Following a suggestion by Merrill, one correction was made to these distances, namely, the absolute magnitudes of the c stars were taken as -5 throughout. Out of eleven such cases the scatter was appreciably reduced in nine and only slightly increased in two. The final diagram gave a rather good linear correlation between K intensity and distance, which indicates for a K intensity of 36 a distance of 950 parsecs. If there were no space absorption, the corresponding absolute magnitude of RS Ophiuchi at maximum would be -5.6.

We have shown that the apparent color temperature of the star is 4,000° and that the photo-electric temperature is about 35,000°. These temperatures are about the same as those generally attributed to K- and O-type stars, respectively. For normal stars of these types Stebbins and Huffer give color indices of $+0.64$ and -0.23. Thus the measured color excess is, in round numbers, $+0.9$. When Rayleigh scattering alone is operative, the visual absorption is about equal to the color excess, so that the absolute magnitude at maximum becomes -6.5. Since there probably is, in addition, some non-selective space absorption, the absolute brightness at maximum exceeds this value.

If the whole intensity of 60 units for K is ascribed to interstellar calcium, we obtain a distance of 1600 parsecs, and a lower limit to the brightness of -7.6.

It remains for us to see whether the observed color can be sufficiently explained by space reddening. On page 243 of their paper, Stebbins and Huffer show, in Figure 5*c*, the color excess per thousand parsecs (E/1000) as a function of galactic longitude. Their observations are rather scanty in the region of the sky near RS Ophiuchi, but

[21] It seems worth noting that on this plate the measured ratio of K to H is only about 1.1.

[22] J. Stebbins and C. M. Huffer, *Pub. Washburn Obs.*, **15**, 217, 1934. Subsequent references to Stebbins and Huffer are to this paper.

from the diagram we may estimate that at galactic longitude 348°, $E/1000 = +0.7$. At a distance of 950 parsecs the star is, therefore, slightly too red for this coefficient, whereas if we adopt the value 1600 parsecs, the corresponding color excess, +1.1, is 0.2 magnitudes greater than the observed. Hence we can say that if we take the distance of the nova as being of the order of 1200 parsecs, its low color temperature may be entirely accounted for by space reddening.

In conclusion, the writers desire to state that the many shortcomings of this work are only too obvious to them. The only extenuation offered is the fact that studies of this nature are at present practically nonexistent. If it does nothing more, this paper may at least serve to emphasize once again the urgent need for careful and complete spectrophotometric investigations of future novae.

CARNEGIE INSTITUTION OF WASHINGTON
MOUNT WILSON OBSERVATORY
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THE SPECTROSCOPIC BINARY α VIRGINIS

By O. STRUVE and E. EBBIGHAUSEN

ABSTRACT

New elements are derived for Spica: $P=4.014160$ days; $e=0.10$; $\omega=40°$; $K=126.8$ km/sec.; $K_2=202$ km/sec.; $\gamma=+0.5$ km/sec.; $T=$J.D. 2426041.26. The period has been constant since 1891. The longitude of periastron seems to have advanced approximately 70° since Baker's observations in 1907–1908. The intensities of the absorption lines of both components vary; each component is strongest when its velocity is at minimum. The total absorption of the fainter component varies in a range of 1.7 to 1, while for the stronger component the range is 1.4 to 1. Three possible explanations are discussed. The interstellar K line is extremely weak.

1. The orbit of this spectroscopic binary was determined by Vogel[1] and by R. H. Baker.[2] The latter found, from measurements of eighty-three spectrograms taken in 1907 and 1908, that the period was 4.01416 days, the eccentricity 0.10 ± 0.014, and the longitude of periastron $328°\pm5°$.

Several months ago Dr. W. J. Luyten requested, in connection with his investigation of the advance of periastron in binaries,[3] that the orbit of Spica ($\alpha=13^h20^m$; $\delta=-10°38'$; mag. 1.2; sp. B2n) be redetermined at the Yerkes Observatory in order to find (1) whether the eccentricity of 0.1 is real, and (2) whether there has been an appreciable change in the longitude of periastron.

2. Spica was observed with the three-prism Bruce spectrograph in 1929 and 1930 for the purpose of determining the axial rotations of the two components.[4] New single-prism plates have been secured in 1933 and 1934, and the results, representing the unweighted means of measurements by the two authors, are given in Table I. The wave-lengths of the stellar lines used in this work are given in Table II.

3. The preliminary elements derived from these observations are shown in Table III. The agreement of our elements with those of

[1] *Pub. Potsdam Obs.*, **7**, 127, 1892.

[2] *Pub. Allegheny Obs.*, **1**, 65, 1909.

[3] *Pub. A.S.P.*, **45**, 297, 1933.

[4] O. Struve, *Ap. J.*, **72**, 1, 1930.

TABLE I

OBSERVATIONS OF α VIRGINIS

Date	U.T.	Velocity I	Velocity II	Quality
1929 Dec. 31	11^h14^m	+131.4	.....	p
1930 Feb. 14	7 50	− 20.6	.....	p
1930 Mar. 3	8 05	−124.0	+196.3	g
1930 Mar. 8	7 30	+ 6.1	.....	g
1930 Mar. 20	6 52	− 6.8	.....	g
1930 Mar. 31	6 41	− 88.8	+200.2	g
1930 Apr. 19	3 38	+ 11.2	.....	g
1930 Apr. 22	4 40	+122.2	−172.8	g
1930 Apr. 22	5 46	+106.5	−170.2	g
1930 Apr. 22	6 53	+101.8	−182.4	g
1930 Apr. 24	4 28	−111.7	+188.5	g
1930 Apr. 24	5 35	−113.0	+181.3	g
1930 Apr. 26	3 25	+111.8	−176.9	g
1930 Apr. 26	4 33	+106.2	−167.4	g
1930 May 1	3 25	− 10.5	.....	p
1930 May 3	2 56	− 61.1	.....	g
1930 May 6	3 41	−109.5	+176.1	g
1930 May 8	2 54	+ 83.3	−135.5	f
1930 May 8	4 01	+107.0	−181.2	g
1930 May 10	2 43	−103.8	+170.4	p
1930 May 10	3 15	−103.4	+168.6	p
1933 Nov. 28	12 23	+ 34.6	.....	g
1933 Nov. 30	11 45	−100.7	.....	p
1933 Nov. 30	12 00	− 98.8	.....	p
1933 Nov. 30	12 11	− 86.4	.....	p
1933 Nov. 30	12 17	− 81.7	.....	p
1933 Dec. 18	12 44	+ 18.8	.....	g
1933 Dec. 27	10 32	+124.3	−221.7	g
1933 Dec. 27	11 02	+130.8	−211.9	g
1934 Jan. 16	11 30	+144.0	−203.5	g
1934 Jan. 20	9 20	+137.5	−195.1	g
1934 Jan. 21	12 29	− 27.3	.....	g
1934 Jan. 27	12 37	− 2.4	.....	g
1934 Jan. 30	11 44	−111.2	+181.2	g
1934 Jan. 30	12 04	−111.2	+181.9	g
1934 Feb. 21	9 24	+130.2	−198.2	g
1934 Feb. 23	9 33	−114.0	+177.4	g
1934 Feb. 23	9 51	−115.2	+179.6	g
1934 Feb. 23	12 14	−107.8	.....	p
1934 Feb. 24	6 21	− 17.9	.....	g
1934 Feb. 24	6 45	− 17.5	.....	g
1934 Feb. 27	7 47	−116.2	+174.8	f
1934 Mar. 9	7 57	+116.1	−192.2	g
1934 Mar. 9	10 05	+136.6	−215.3	g
1934 Mar. 10	7 11	+ 9.2	.....	g
1934 Mar. 13	7 02	+117.0	−193.8	g
1934 Mar. 13	7 52	+120.1	−207.6	g
1934 Mar. 19	7 29	−115.9	+197.0	g
1934 Mar. 19	7 46	−114.0	+182.9	g
1934 Apr. 10	5 28	+107.2	−173.9	g
1934 Apr. 10	5^h42^m	+113.0	−174.7	g
1934 Apr. 12	6 18	−119.8	+188.9	g
1934 Apr. 16	7 02	−106.5	+170.8	g
1934 Apr. 26	3 35	+ 52.0	.....	g
1934 Apr. 26	4 11	+ 61.6	.....	p
1934 Apr. 30	4 49	+ 83.9	−161.9	g
1934 Apr. 30	5 09	+ 88.0	−140.4	g
1934 May 2	5 53	−110.7	+173.8	g
1934 May 2	6 09	−111.0	+162.7	g
1934 May 4	6 07	+ 90.8	−165.8	g
1934 May 4	6 28	+ 88.4	−132.4	p
1934 May 8	4 21	+ 66.6	− 98.2	g
1934 May 8	4 36	+ 64.3	− 96.4	g
1934 May 14	3 59	−102.8	+165.6	g
1934 May 14	4 23	−115.2	+139.2	g
1934 May 16	3 49	+ 39.8	.....	g
1934 May 16	4 14	+ 44.9	.....	g
1934 May 18	3 58	−102.1	+154.6	g
1934 May 19	4 00	− 88.0	+123.3	g
1934 May 27	1 56	−114.2	+151.1	g
1934 May 28	4 35	+ 43.7	.....	g
1934 May 30	1 48	− 78.8	.....	g
1934 June 5	4 41	+ 46.6	.....	f
1934 June 5	4 56	+ 39.9	.....	f
1934 June 7	2 01	− 61.8	.....	g
1934 June 10	2 05	+142.8	−199.6	p
1934 June 11	1 56	− 54.9	+ 82.9	g
1934 June 13	3 08	+ 9.7	.....	g
1934 June 25	1 57	− 8.2	.....	g
1934 June 25	2 09	− 7.4	.....	g
1934 June 27	2 49	− 58.4	.....	g
1934 June 29	2 05	− 3.4	.....	g
1934 June 30	1 53	+134.6	−196.8	f
1934 June 30	2 01	+139.8	−215.8	g
1934 June 30	2 14	+133.5	−211.7	g
1934 June 30	2 25	+138.5	−208.8	g
1934 June 30	2 36	+124.8	−217.8	g
1934 June 30	2 54	+133.8	−190.3	g
1934 June 30	3 30	+112.1	−209.3	p
1934 June 30	4 18	+113.2	−201.5	p
1934 July 2	2 04	−108.2	+178.8	g
1934 July 2	2 17	−122.2	+158.4	g
1934 July 2	2 29	−110.6	+153.6	g
1934 July 3	2 12	− 5.8	.....	g
1934 July 4	2 10	+131.6	−214.0	f
1934 July 12	2 04	+139.0	−194.9	g
1934 July 12	2 14	+136.2	−206.8	g
1934 July 14	2 07	−113.4	+165.6	g
1934 July 14	2 30	−107.7	+171.6	g

Baker is excellent, except in the case of ω and T. The velocity-curve is unsymmetrical, and ω seems to have advanced approximately

TABLE II

STAR LINES

He I 4009.27	*C* II 4267.16	*Si* III 4552.61
He I 4026.19	*Hγ* 4340.47	*Si* III 4567.82
Hδ 4101.74	*He* I 4387.93	*Si* III 4574.74
He I 4120.81	*He* I 4471.48	*Hβ* 4861.33
He I 4143.76	*Mg* II 4481.23	

70°. A further analysis of this advance in periastron will be undertaken by Dr. Luyten.

TABLE III

ORBITAL ELEMENTS

	Struve and Ebbighausen	Baker
P	4.014160 days	4.01416 days
e	0.10	0.10
T	J.D. 2426041.26	1908 Jan. 14.846
ω	40°	328°
K_1	126.8 km/sec.	126.1 km/sec.
γ	+0.5 km/sec.	+1.6 km/sec.
$a_1 \sin i$	6,965,000 km	6,930,000 km
K_2	202 km/sec.	207.8 km/sec.
$a_2 \sin i$	11,096,000 km	11,400,000 km
m_2/m_1	0.63	0.61
Minimum velocity	J.D. 2426038.72	J.D. 2417958.29

Figure 1 shows the velocity-curves by Baker and by the authors. Zero phase corresponds to the Yerkes time of periastron passage. Baker's curve was adjusted in phase to correspond to the Yerkes curve at $V=\gamma$. The blended observations are unreliable for the determination of the orbit; the fainter component markedly displaces the blended line toward the γ-axis.

4. Plotting the individual observations by Vogel and by Baker with the latter's period, we find the following three epochs of minimum velocity:

Series	Minimum Velocity
Vogel, 1890–1891	J.D. 2411495.42
Baker, 1907–1908	2417958.29
Yerkes, 1929–1934	2426038.72

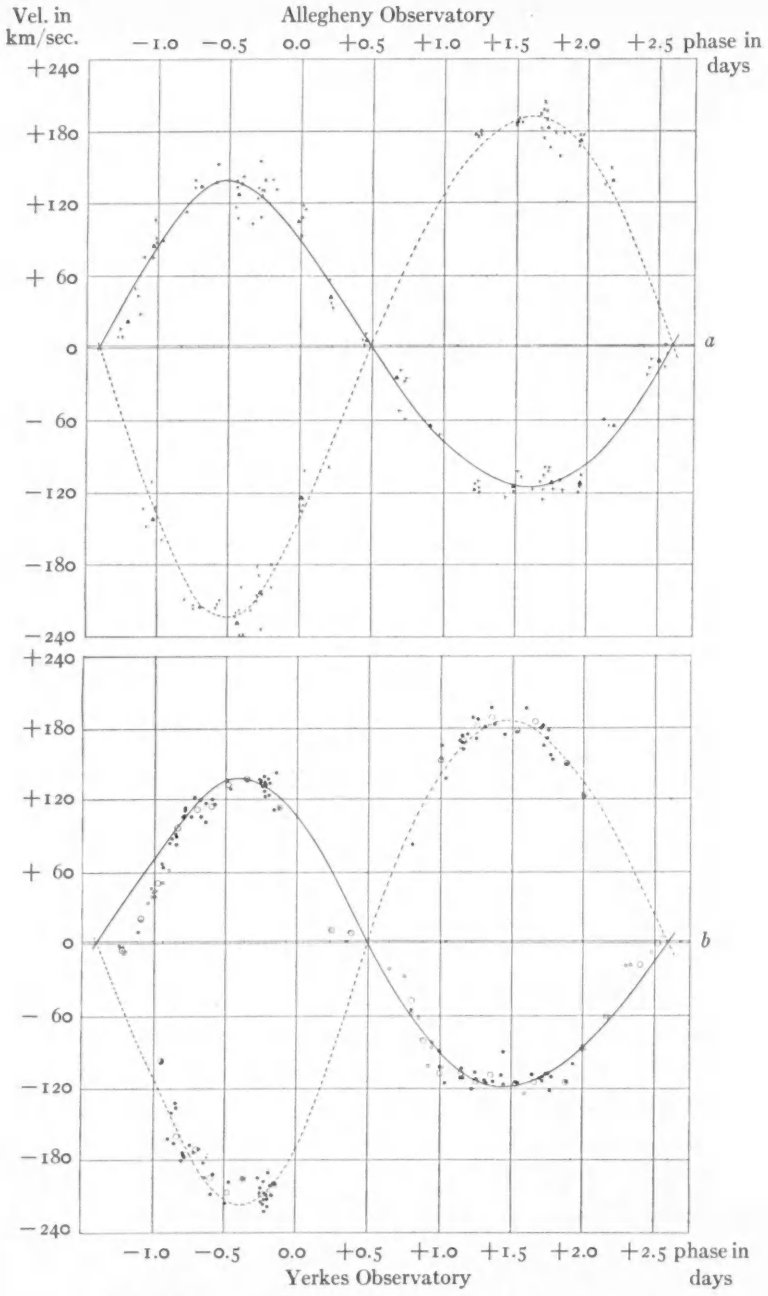
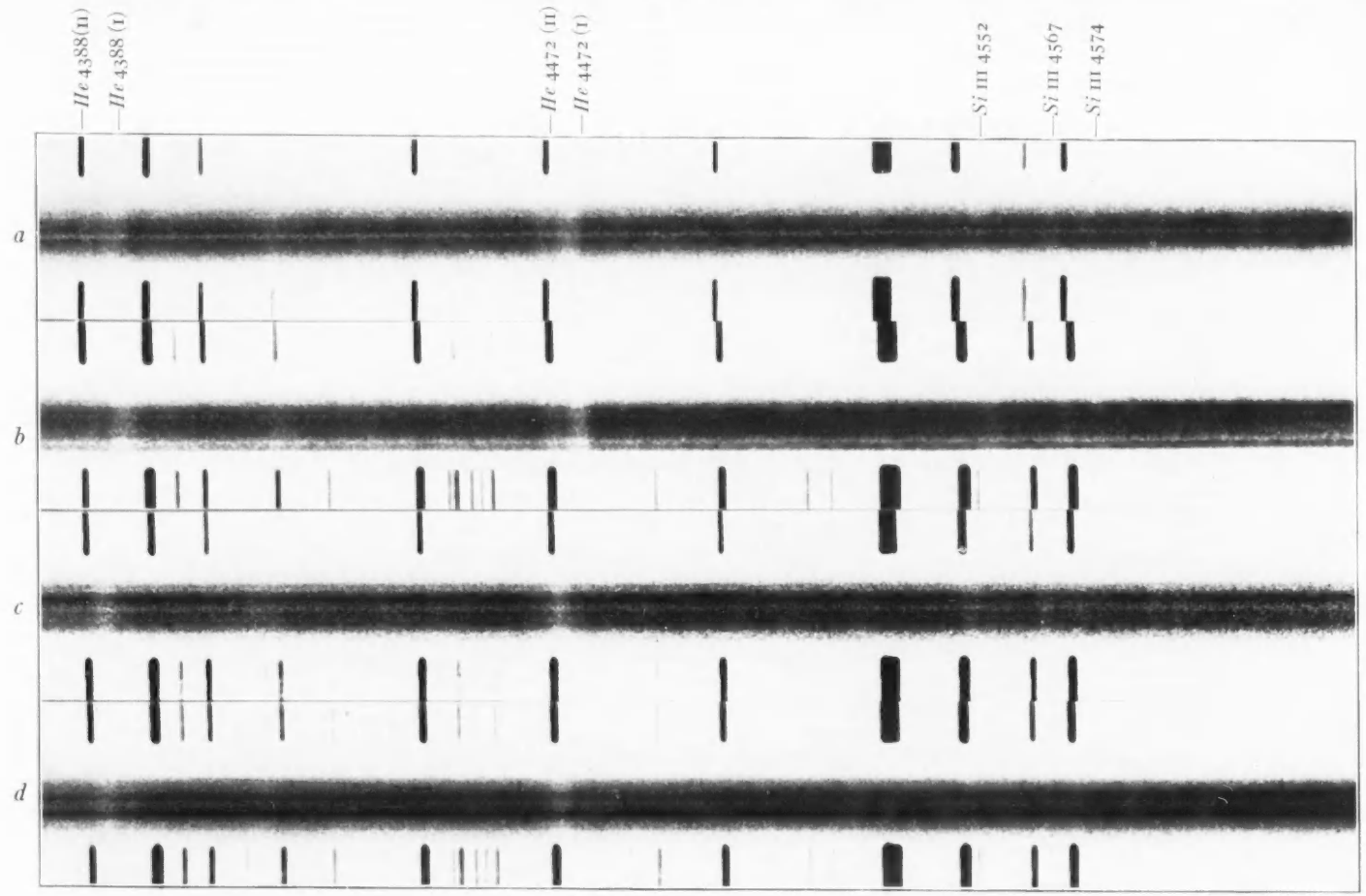


FIG. 1.—(*a*) Allegheny Observatory velocity-curve: + stronger component; × weaker component; ⊢ blended lines; ▲ normal points; (*b*) Yerkes Observatory velocity-curve: ● complete observations; o blended lines; O normal points.

PLATE V



SPECTRUM OF α VIRGINIS

a) 1934 Jan. 16, 11^h30^m U.T. (phase 3^d75); *b*) 1934 July 12, 2^h14^m U.T. (phase 3^d74); *c*) 1934 May 2, 6^h09^m U.T. (phase 1^d16); *d*) 1934 March 19, 7^h46^m U.T. (phase 1^d37).

The total number of revolutions between the first epoch and the last is 3623. The corresponding period is 4.014160 days, in exact agreement with Baker. Using this value, we find that the number of revolutions between the second and the last epoch is 2013. The computed interval is 8080.50 days, while the observed interval is 8080.43 days. The difference is 0.07 day, which, spread over two epochs, is not large enough to be detected with certainty. We thus conclude that, within the precision of the measurements, the period has been constant between 1890 and 1934.

5. In the course of this investigation we found a remarkable periodic change in the relative intensities of the two absorption components of Spica. Generally speaking, the fainter component is much less intense with respect to the brighter when the former recedes from the sun and the latter approaches it (Pl. V).

Whether this phenomenon was caused by a change in the fainter component alone, or by changes in both components, could only be ascertained by a careful examination of the entire material.

The effect is seen best when the two components are completely separated. At our request Miss Lois T. Slocum has made estimates of the line intensities for all plates on which the radial velocity of the primary component is $\lesssim \pm 80$ km/sec. The corresponding intervals of phase are approximately 3.2–0.1 day and 0.9–2.0 day. The estimates were made on an arbitrary scale. For the faint component *He* 4472 was estimated. The strong component of this line is unsuitable because of its great intensity. Accordingly, the *Si* III line 4552 was used for the strong component. By means of several microphotometer tracings the estimates were later converted into total absorptions expressed in A-units of complete darkness. The calibration was found to be

Estimate	0	1	2	3	4
Total absorption in A	0.10	0.12	0.17	0.24	0.38

The results[5] of the estimates are given in Table IV.

Both components vary, but the variation is appreciably greater for the fainter component.

[5] The values given in Table IV are tentative. The measurement of faint diffuse lines is difficult and the probable errors are large.

We have attempted to plot the estimated intensities against phase within each of the phase intervals. There is no systematic difference within these intervals. In other words, the maximum and minimum intensities of each component coincide, within the rather limited precision of the estimates, with the minimum and maximum velocities of each component.

A test of possible secular changes in the intensities was also made, but the result was negative. The observed variations appear to repeat themselves precisely with the period of the binary.

An examination of the plates taken when the two components are blended showed that in phase interval 2.3–3.0 days the fainter component is usually seen as a rather narrow line superimposed over

TABLE IV

	Estimate	Total Absorption
STRONG COMPONENT, λ 4552		
Positive velocity of strong component > +80 km/sec.	2.0	0.17 A
Negative velocity of strong component < −80 km/sec.	3.0	0.24
Ratio	...	1.4
FAINT COMPONENT, λ 4472		
Positive velocity of strong component > +80 km/sec.	2.6	0.20
Negative velocity of strong component < −80 km/sec.	0.9	0.12
Ratio	...	1.7

the wing of the broader and stronger component. In the phase interval 0.2–0.8 day this is not so clearly shown, but there are only a few good plates and the result is therefore not decisive. We suspect that the total intensities of the blended lines are slightly stronger in phase interval 2.3–3.0 days than in phase interval 0.2–0.8 day.

We also suspect that the contour of the stronger component is not always that demanded by the rotational effect, but that occasionally the edges of the line are steeper than would be expected. Unfortunately, our single-prism spectrograms, though taken on a high-contrast emulsion and properly widened, do not suffice to bring out clearly these details in the line contours. This work will be continued with the use of three-prism spectrograms.

The contour of the fainter component is narrow when its velocity is positive. This feature has already been discussed by Struve.[4] It

should be noted, however, that in his work on the rotational velocities of the components of α Virginis, he used only spectrograms on which the faint component was displaced toward the red. Our new plates indicate that the contour of the fainter component is not so narrow when its velocity is negative, although even then it is not nearly as wide as the stronger component. In view of this variation in line width, the ratio of the diameters found by Struve from the relative widths of the two components cannot be regarded as definitely established.

6. The phenomenon which we have described in section 5 resembles that discovered by Bailey[6] in the spectrum of the binary μ^1 Scorpii. A brief description of this was given by Miss Cannon,[7]

TABLE V

	P	K_1	e	ω	Variation in Line Intensity
μ^1 Scorpii	$1^d.446$	200?km	0.05	190°	Strong
V Puppis	1.454	300?	.08	72	Strong
π Scorpii	1.571	138	.05	90	Suspected
σ Aquilae	1.950	164	.0	.....	Absent
2 Lacertae	2.616	80	.01	180	Suspected
α Virginis	4.014	127	0.10	40	Average

and a complete study has recently been published by Miss Maury.[8] The latter also discovered a similar variation in the lines of V Puppis.[9]

From Miss Maury's description it appears certain that the variations in the intensities of the two components of μ^1 Scorpii and of V Puppis greatly exceed those of α Virginis.

The fact that three spectroscopic binaries of short period and large amplitude of velocity show the same phenomenon suggests that it may be caused by similar physical changes in close double stars.

In Table V we have listed several short-period spectroscopic binaries of class B having double lines. Evidently the variations are not correlated in any simple manner with either period or amplitude. They are certainly much weaker in π Scorpii than in V Puppis and

[6] *Harvard Circ.*, **11**, 1896.

[7] *Harvard Ann.*, **28**, Part II, remark 73.

[8] *Ibid.*, **84**, 169, 1920.

[9] *Ibid.*, p. 178.

in μ^1 Scorpii. They are not related to ω, which is 190° in μ^1 Scorpii and 40° in α Virginis, and are therefore not an effect of periastron like the one recently discovered by Morgan in μ Sagittarii[10] and later verified by him with the help of a large amount of new material. This latter effect produces striking changes in the stronger helium lines near periastron. It should be remembered, however, that for μ Sagittarii, $P=180$ days, $e=0.45$, so that obviously this is an entirely different phenomenon from that observed in α Virginis.

The material is hardly sufficient to permit a complete interpretation of these variations. Three possible mechanisms suggest themselves:

a) The phenomenon resembles that postulated many years ago by Duncan for the explanation of the light-curves of Cepheid variables.[11] The two components are supposed to have identical periods of rotation and orbital revolution. Their motion in a resisting medium would heat the advancing side of each component, thus causing a variation in the intensities of the two continuous spectra.

According to this hypothesis, the variation is entirely due to changes in the continuous spectra and not to the lines themselves. The amount of absorbing matter is considered equal in all four spectra. This presupposes, of course, that the spectral types of the two components are the same. Let the total absorptions of the lines be $A_1'=A_2'=A_1''=A_2''=A$, and let the intensities of the continuous spectra of the two sides of component one be C_1' and C_2' while the intensities of the continuous spectra of component two are designated C_1'' and C_2'', for the fainter and the brighter side, respectively. The observed continuous spectrum is $C_1'+C_1''$ when the velocity of the primary is negative and $C_2'+C_2''$ when the velocity of the primary is positive. The observed intensities of the four lines are

$$\frac{AC_1'}{C_1'+C_1''}=a\,; \qquad \frac{AC_1''}{C_1'+C_1''}=b\,; \qquad \frac{AC_2'}{C_2'+C_2''}=d\,; \qquad \frac{AC_2''}{C_2'+C_2''}=e\,.$$

[10] *Ap. J.*, **75**, 407, 1932.

[11] This hypothesis has, of course, been abandoned in so far as the Cepheids are concerned.

The data in Table IV give

$$\frac{a}{d}=1.4\,; \qquad \frac{e}{b}=1.7\,.$$

Furthermore, Struve[4] found

$$\frac{a}{b}=8.8\,.$$

It is, of course, obvious that the observations can give only the two ratios C_1'/C_1'' and C_2'/C_2''. We cannot derive C_1'/C_2'. In other words, the observed intensities depend upon the ratios of intensity of the bright side of the primary to the faint side of the secondary, and of the faint side of primary to the bright side of the secondary, but they tell us nothing concerning the quantity $m=C_1'/C_2'$. If m is known from other data, then we also know C_1''/C_2''.

It is seen that

$$\frac{C_1'}{C_1''}=\frac{a}{b}=8.8\,.$$

Forming

$$\frac{a}{d}=1.4=\frac{1+\dfrac{C_2''}{C_2'}}{1.11} \qquad \text{and} \qquad \frac{e}{b}=1.7=\frac{9.8}{\left(\dfrac{C_2'}{C_2''}+1\right)}\,,$$

we find two values of C_2''/C_2':

$$\frac{C_2'}{C_2''}=1.8\,; \qquad \frac{C_2'}{C_2''}=4.8\,,$$

which are inconsistent with one another. We conclude that the observations given in Table IV are not consistent with the hypothesis $A_1'=A_2'$; $A_1''=A_2''$. This may, however, be due to the lack of precision in our observations.

We shall tentatively adopt $C_2'/C_2''=3.5$. Supposing next that the stronger component does not vary at all ($m=1$), we find $C_2''/C_1'=2.5$. The bright side of the companion is 2.5 times more intense than the faint side.

The spectral class of each of the two components is B2, corresponding roughly to $T''=15{,}000°$ K. Computing from Planck's law the temperature corresponding to an increase in $J(\lambda)=C_1\lambda^{-5}(e^{C_2/\lambda T}-1)^{-1}$ by a factor of 2.5, we find for $\lambda=5000$ A

$$T'=25{,}000° \text{ K}.$$

Such a large difference between T' and T'' should produce a marked difference in the spectral types of the two sides of the companion, which is contrary to observation.

Another objection to hypothesis (*a*) is the mechanical difficulty of accounting for so large a difference in temperature. The energy required is so enormous that the density of the resisting medium would have to be much greater than could be reconciled with the fact noted in section 4, that the period has been constant to within at least 0.00001 day (or 1 sec.) in an interval of forty-four years.[12]

b) It might be suggested that the variation of the intensities is caused by the reflection effect in a close binary. Eddington[13] has given a formula for computing the amount of light reflected from the companion, when C'/C'' and $\varphi=R_2/a=$radius of companion/distance of centers are known. For several eclipsing variables the brighter side of the companion is twice as intense as the fainter side. For α Virginis R_2/a is not accurately known, but, assuming a reasonable value for this ratio, it seems probable that the reflected light would make an important contribution to the total brightness of the companion.

If the two components are spherical, or if they are ellipsoids having their major axes in the line joining their centers, then the reflection effect at both quadratures is the same and the fainter component should be strongest at opposition. The observations prove that the effect at the two quadratures is not the same.

If there is no equality in the periods of rotation and revolution, tidal lag will cause the major axes to be displaced from the line

[12] It is easy to apply to the present case the argument advanced by H. Poincaré (*Leçons sur les hypothèses cosmogoniques*, p. 194, 1913) against the meteoric hypothesis of the maintenance of the sun's heat.

[13] *Internal Constitution of Stars* (German ed.), p. 263, 1928.

joining the centers.[14] In that case the reflection effect will not be the same in the two quadratures. However, maximum and minimum line intensity should occur somewhere between quadrature and opposition, and not at quadrature as observed.

Furthermore, the ellipticity of the components of close binaries is usually small, and while the reflection effect in the companion may be observable in opposition, it will produce but little difference in the two quadratures. The ellipticity of α Virginis has not been determined, but Stebbins[15] found a probable variation in light amounting to about 0.10 mag. Judging from the somewhat similar case of the variable π^5 Orionis for which Stebbins[16] finds an elongation of only a little more than 5 per cent, we can conclude that the ellipticity of the stronger component in α Virginis is insufficient to cause the observed variation in the line intensities. There remains, however, the possibility recently discussed by K. Walter,[17] that the ellipticity of the fainter component is different from that of the stronger.

c) The third hypothesis attributes the changes to an actual increase of absorbing gas on the advancing side of each component. There is no theoretical explanation for this increased thickness, but, accepting it as a working hypothesis, we estimate that the amount of material on the advancing side of the reversing layer of each component is roughly twice that on the receding side.

7. The peculiar variations in the intensities of the components make it somewhat uncertain whether the position of each component as measured under the microscope is actually a true measure of the velocity of the center of gravity of each star. It is possible that the contour of each component is unsymmetrical and that the amount of asymmetry varies. In that case a spurious eccentricity may easily be introduced into the orbit.

However, there is at present no real reason to suspect such a spurious effect. The value of ω in α Virginis is 40°, while in μ^1 Scorpii it is 190° and in V Puppis, 72°. Apparently the eccentricity

[14] J. H. Jeans, *Astronomy and Cosmogony*, p. 286, 1928.

[15] *Ap. J.*, **39**, 478, 1914.

[16] *Ibid.*, **51**, 218, 1920.

[17] *Veröff. Sternwarte Königsberg*, No. 2, 1931; *ibid.*, No. 3, 1933.

of the orbit is not caused by the spurious shifts of unsymmetrical lines, for otherwise we should expect that ω would be the same in all stars, and that, furthermore, e would be larger in μ^1 Scorpii and in V Puppis than in α Virginis, since in the two former stars the intensities vary over a much larger range than in the latter.

Another argument in favor of the reality of e is the variation in ω detected in α Virginis.

8. The interstellar calcium line in α Virginis is exceptionally weak. We have taken a Process plate with the spectrum widened several millimeters. The interstellar line is barely visible, and its intensity leads us to expect that the distance of α Virginis is small. Assuming the density of the interstellar cloud to be uniform, the distance of the star could hardly exceed 100 parsecs, and should probably be in the neighborhood of 50 parsecs.

The galactic latitude of α Virginis is $+50°$, and it is therefore possible that the density of the interstellar calcium should not be considered uniform.

9. In presenting this brief study of the orbit and the spectral changes of α Virginis, we have attempted to emphasize the importance of a careful study of known spectroscopic binaries. Not only do the orbital elements merit a redetermination, but physical changes have now been established in these close double stars which are still extremely puzzling.

We are indebted to Miss Slocum for the estimates of the line intensities.

YERKES OBSERVATORY
August 27, 1934

A STUDY OF THE SOLAR PROMINENCE OF JULY 18, 1933

By PAUL RUDNICK

ABSTRACT

Thirty-seven calcium spectroheliograms taken with the 40-inch refractor on July 18, 1933, give the history of an active prominence over a period of five and one-third hours. The prominence consisted mainly of very low arches. The motions are described in some detail, and are correlated with spectrohelioscope observations of radial velocities. The movements appear to be connected with the development of two centers of attraction quite near the limb. During the period of observation the prominence involved and distorted a neighboring quiescent prominence.

Blink comparator measures give internal velocities up to about 60 km/sec. for a few knots, although most of the velocities measured were less than half that value. The prominence when considered in detail shows some turbulence. However, the majority of the displacements measured were nearly parallel to the limb, as the material was moving along the flat arches making up the prominence. Some measurements of motions and heights of the quiescent prominences were also made.

Thirty-seven spectroheliograms of the interesting active prominence of July 18, 1933, were obtained by the writer with the Rumford spectroheliograph attached to the 40-inch refractor of the Yerkes Observatory. They were taken in the H line of ionized calcium. The plates cover an interval of five and one-third hours; all but three were taken, however, in the first three hours of this time.

Observations with the spectrohelioscope at 13^h45^m U.T. showed a mass of unusually bright material touching the west limb at a position angle of about 20° N. (Some 12°–15° farther north there were two quiescent prominences which had been visible for three days previously.) This prominence first had the shape of two low arches—a very low one extending toward the south from the point where they touched the limb, and a longer, higher one leading toward the tops of the two quiescent prominences on the north.

Exposures with the spectroheliograph were begun at $15^h03^m.6$ U.T. (the time of this first exposure will be denoted by t in what follows) and repeated at average intervals of $4^m.8$ until $17^h53^m.1$ ($t+2^h49^m.5$). Three additional exposures were made later in the day, between $20^h11^m.0$ ($t+5^h07^m.4$) and $20^h21^m.5$ U.T. ($t+5^h17^m.9$).

On the first exposure the active prominence consisted of a rather

low arch extending north from a region (Pl. VI, *A*, exposure *b*) on the west limb almost as far as the top of the quiescent prominence 180,000 km away (*B*, exposure *b*), and another flat arch to the south, touching the limb again at a distance of 66,000 km. Farther south were some faint, fine, arched streamers, touching the limb near the south end of the second arch. These remained in almost the same place during the whole period, sending material into a center of attraction at a position angle about 11° N. (*C*, exposure *b*). The two main arches covered some 17° of the limb, as may be seen in exposure *b*. Matter in the main arches of the prominence seemed in general to be moving away from the point *A* on the limb toward the top of the neighboring quiescent prominence, in the first few exposures. The spectrohelioscope showed a 60 km/sec. velocity of recession of the north end of the main arch at 15^h08^m ($t+4^m$), suggesting that this material was moving toward the quiescent prominence, the latter being beyond the limb. The material near point *A* on the limb, on the other hand, showed radial velocities from 0 to −50 km/sec. at 15^h05^m U.T. ($t+1^m$). By $15^h14^m.0$ U.T. ($t+10^m.4$) the gap between the arch and the quiescent prominence *B* was closed, as may be seen on Plate VII, exposure *f;* but in the next exposure, *g*, taken at $15^h20^m.6$ ($t+17^m.0$), the upper part of the active prominence had faded out almost completely; the arched outline of the top terminated at the base, rather than at the summit, of the quiescent prominence, material seemingly being pulled into a center of attraction on the limb around position angle 30° N. (Pl. VI, *D*, exposure *c*). At 15^h32^m ($t+28^m$), nearly the whole prominence showed radial velocities from 0 to −30 km/sec.; only small parts showed as much as 26 km/sec. velocity of recession. By 15^h41^m ($t+37^m$), only small patches showed at −30 km/sec. This is the last measure of radial velocity.

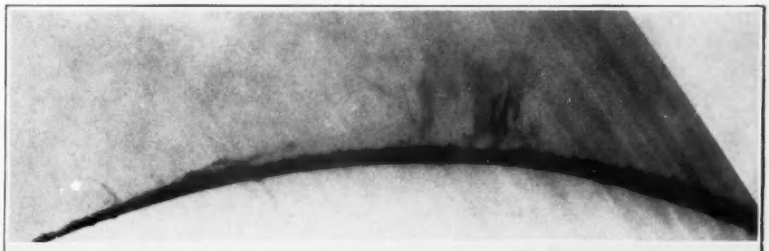
During the next phase of the activity, matter appeared to pile up at the foot of the quiescent prominence (see exposure *d*, taken at $15^h50^m.6$ U.T. or $t+47^m.0$), finally involving and distorting the top part of the latter around 16^h U.T. ($t+57^m$). Meanwhile, the density was decreasing steadily in that part just north of the point *A*, from which the material appeared to come. The arch south of this point did not change a great deal; between this arch and the

PLATE VI

July 17, 1933

a

Exposure at 20^h17^m7 U.T.

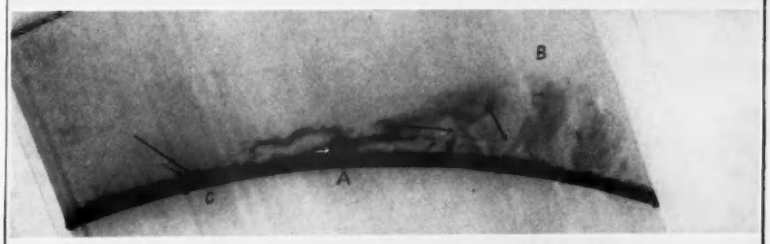


July 18, 1933

Exposure at 15^h06^m1 U.T.

Displacements shown 15^h03^m6 to 15^h24^m1 U.T.

b



Exposure at 15^h24^m1 U.T.

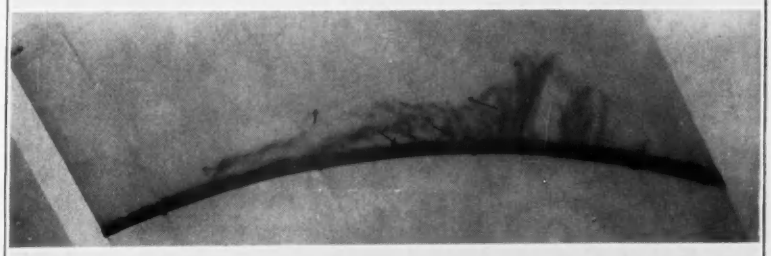
Displacements shown 15^h30^m1 to 15^h50^m6 U.T.

c

Exposure at 15^h50^m6 U.T.

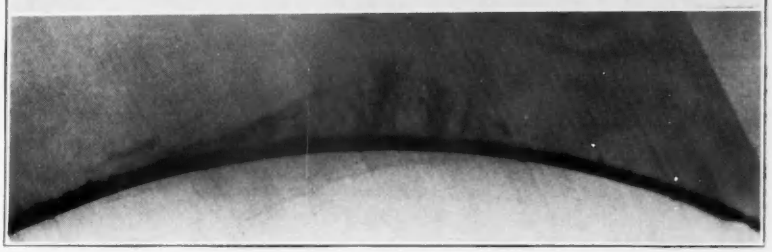
Displacements shown 10^h00^m0 to 16^h20^m2 U.T.

d



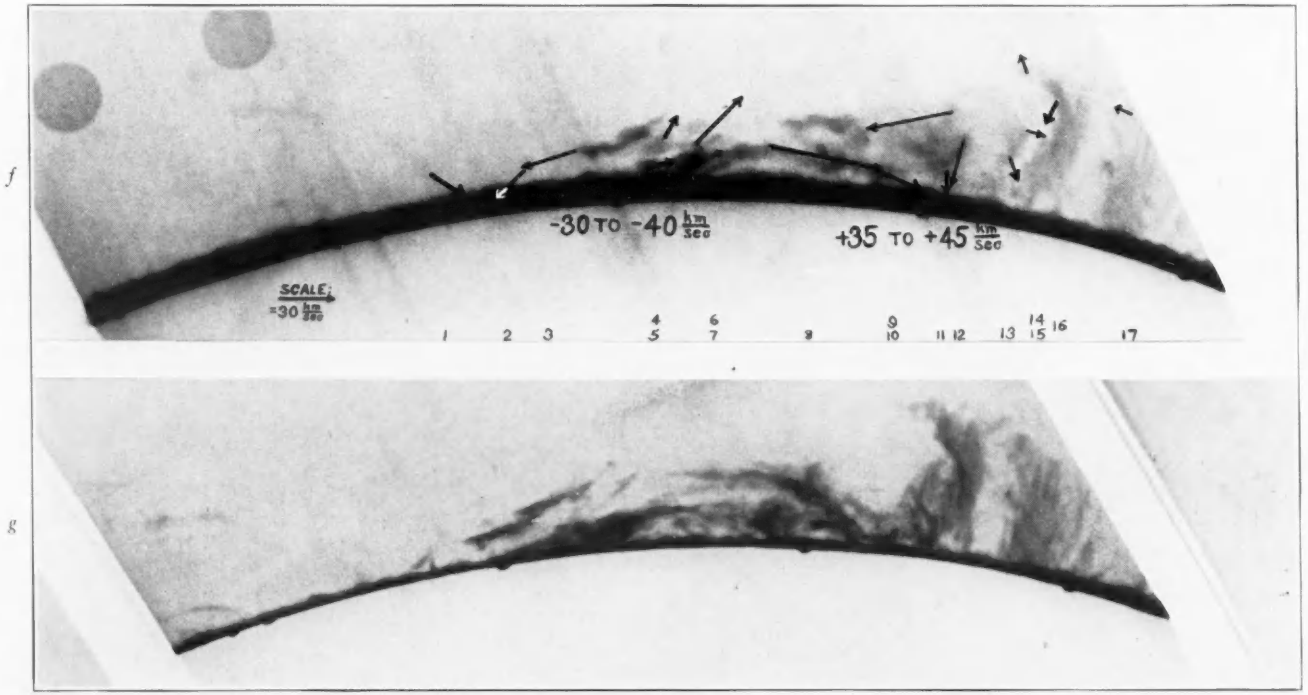
Exposure at 16^h52^m1 U.T.

e



SPECTROHELIOGRAMS OF THE PROMINENCE OF JULY 18, 1933

PLATE VII



PHOTOGRAPHS MADE AT 15^h14^m0 AND 15^h20^m6, 6^m6 APART, SHOWING RAPID CHANGES IN THE PROMINENCE OF JULY 18, 1933

Vectors represent velocities on the scale indicated. Radial velocities from spectrohelioscope measures are given below the region to which they pertain.

material on the north, therefore, there appeared a gap which reached its greatest length at about 16^h20^m U.T. ($t+1^h16^m$) and then began to close again. By 16^h52^m ($t+1^h48^m$) it had closed entirely. For the next hour the prominence maintained roughly the same shape, that shown in exposure *e*, taken at $16^h52^m.1$ ($t+1^h48^m.5$), although losing some height and fading slightly. It covered at this stage some 19° of the limb.

During this time the low arch on the south faded; by $17^h46^m.5$ U.T. ($t+2^h42^m.9$) it was very weak. It did not appear on the last three exposures. Atmospheric unsteadiness and the wind shaking the telescope entirely wiped out all fine detail on these three spectroheliograms, taken about 20^h15^m ($t+5^h11^m$); however, the northern two-thirds of the prominence, covering about 13° of the limb, still showed the same general shape as at 17^h45^m ($t+2^h41^m$), although the rest had faded or dropped to almost nothing.

In general, the story seems to be this: Two bright arches were built up over a period of several days. A sudden uprush of matter during the development of a center of attraction on the disk slightly in front of the limb (*C*, exposure *b*) sent one arch upward and outward until it involved a neighboring prominence, when it faded somewhat, brightened while another center of attraction beyond the limb was coming into play (*D*, exposure *c*), and then faded again to some extent. Meanwhile, the other arch stayed substantially the same for some time and then faded. The faint streamers farthest south showed no appreciable change in shape on the exposures on which they appeared.

The quiescent prominences to the north of this active one were observed with the spectrohelioscope and the spectroheliograph at the east limb on July 3, and with the spectrohelioscope on July 4 and 5. This indicated considerable length in the line of sight, which is confirmed by their presence on spectroheliograms from July 15 to July 19, at the west limb, reaching maximum apparent height on July 17, the day before the activity on the south (see exposure *a*, taken at $20^h17^m.7$ U.T. on July 17). These prominences seemed, on the whole, to be very stable, except when one of them was being pulled around by the active prominence on July 18.

The apparent motion of the whole quiescent prominence along

the limb was measured by comparing the first and last exposures of July 18 in the blink comparator. It proved to be small, only 15,000 km, an average of less than 1 km/sec. The variation in apparent height was somewhat larger; heights of the crest were measured with a transparent scale, and showed a rise from around 72,000 km on the first exposures to a maximum of 79,000 km at 16^h15^m U.T. ($t+1^h11^m$), then a drop to 58,000 km at 17^h40^m U.T. ($t+2^h36^m$), giving a velocity of descent of 4 km/sec., constant within the errors of measurement. The last height was apparently maintained, as the three afternoon exposures give an average height of 60,000 km for the crest.

The height of the topmost part of the active prominence stayed between 45,000 and 50,000 km most of the time, although on three exposures it reached a height slightly over 60,000 km (at 15^h06^m1, 16^h15^m5, and 20^h11^m0 U.T., or $t+2^m5$, $t+1^h11^m9$, and $t+5^h07^m4$, respectively).

All points that could be followed fairly certainly over an interval of several exposures were marked and measured with the blink comparator, using the scales in X and Y. The method was to set the dust lines on both plates parallel to the X-direction, and then to measure displacements, using the base of the northern quiescent prominence as an index. In a few cases this method was modified to make the limb farther south match better. The displacements were converted to distance and position angle (relative to the limb under the point being measured) by graphical means. When it was desired to compare two exposures taken on the same plate, a contact positive and a second negative were made on plates of the same emulsion as the originals (Eastman 33). Upon repeating some of these measures with the blink comparator after several days, the probable error of a setting was found to be approximately 0.1 mm in either co-ordinate. The scale of the plates is $10''.59$ per mm or 7790 km/mm at the date of this prominence. On exposures b, c, and d displacements are plotted covering intervals of $20^m.5$, $20^m.5$, and $20^m.2$, respectively, beginning within ten minutes, one way or the other, of the exposure shown.

A study of the distribution of these displacements in position angle with respect to the limb shows about a 4:1 preference, among

points having clear-cut motions of any kind, for directions parallel to the limb over radial directions. This might be expected in a prominence consisting of such very low arches. Of these motions parallel to the limb, at least two-thirds are toward the north, that is, toward the high quiescent prominence.

Velocities were derived for all points showing clear-cut motion. Twenty-one out of a total of twenty-nine of these were found to lie between 10 and 30 km/sec.; only one point (No. 8, exposure *f*) moving faster than 36 km/sec. was found. This showed a speed of 59 km/sec. over a period of seventeen minutes. Enough conflicting directions of internal motion were found to show that considerable

TABLE I

DISPLACEMENTS AND VELOCITIES FOR AN INTERVAL OF 6^m6

Point No.	Displacement in Km	Velocity in Km/Sec.	Point No.	Displacement in Km	Velocity in in Km/Sec.
1	9100	23.0	10	9900	25.0
2	8400	21.0	11	5200	13.0
3	12500	31.0	12	11100	28.0
4	5600	14.0	13	5500	14.0
5	6400	16.0	14	3900	9.8
6	14600	37.0	15	3900	9.8
7	2500	6.3	16	5000	13.0
8	24800	63.0	17	3300	8.3
9	18800	48.0			

turbulence may appear in a prominence with fairly high internal velocities.

Exposures *f* and *g*, Plate VII, made at 15^h14^m0 and 15^h20^m6 U.T. ($t+10^m4$ and $t+17^m0$), showed very great differences, owing probably in part to changing atmospheric conditions; but examination with the comparator showed that the greater part of the change was probably real. Displacements were measured with especial care, therefore, and velocities were computed. These are given, together with the number of each point as shown on exposure *f*, in Table I.

What seems perhaps the most striking feature of this active prominence is the great accentuation of horizontal motions compared with vertical ones. This indicates, for several of the fastest-moving points measured, an excellent balance between gravita-

tional attraction and supporting force during the period that the material was moving along the very flat arches composing the prominence.

Another interesting feature, very possibly an effect of projection, is the occurrence quite close together of knots or condensations moving in entirely different directions; this gives the effect of strong turbulence.

From the general sequence of events one may infer that the two quiescent prominences on the north were past the limb, since they reached their maximum apparent height on the previous day; they may have been about 250,000 km beyond the limb. The active prominence, on the other hand, was probably not far beyond the limb, as it showed steady increases in height on spectroheliograms taken on July 15, 17, and 18. The same relative positions could be deduced from the apparently close approach of the activity toward the quiescent prominence before the latter was disturbed, and from the strong positive radial velocity of the top of the active arch at the time of the disturbance, which must have carried that part at least 50,000 km away from the earth and probably toward the quiescent prominence.

Fairly high velocities were maintained for appreciable periods of time by some points in this active prominence. This fact seems to confirm a feature found by previous observers, namely, that prominences maintain their general shape longer than a given mass of material stays in them; there seems to be a continuous interchange of material between prominence and chromosphere.

Dr. P. C. Keenan and Mr. J. L. Halpern made the observations with the spectrohelioscope and assisted in the photographic work. The author wishes to thank Dr. Keenan and Dr. E. Pettit for helpful suggestions.

YERKES OBSERVATORY
August 24, 1934

REVIEWS

The Design and Use of Instruments and Accurate Mechanism. By T. N. WHITEHEAD. New York: Macmillan Co., 1934. Pp. xii+283. $3.50.

While this book will appeal primarily to those who use instruments, it should be of value to both users and designers. To quote from the preface: "Thus the present book represents a conscious revolt against mathematical abstraction when unaccompanied by an independent examination of the actual facts." The need for assessing the similarity of the mathematician's ideal to reality is stressed. Because of comparative lack of mathematical facility, the engineer and designer are too ready to accept the conclusions of a train of reasoning without sufficiently examining the relevance of its assumptions—a subject on which he, and not the mathematician, is the expert. For example, the theory of errors as evolved from the theory of probability has only limited application.

After discussing errors and their sources at length, the author considers the advantages and disadvantages of kinematic design and comes to the conclusion that a type of design that he calls semikinematic can be made to possess the advantages of kinematic design while at the same time avoiding the undesirable features. Throughout the discussions well-known existing instruments are taken as illustrations. In the closing chapters several measuring machines are analyzed, while in the last chapter the human factor in precise measurements is treated in a manner that should be well worth perusal by all who have much measuring to do.

G. W. MOFFITT

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